Sources of Nuclear Fuel

U. S. ATOMIC ENERGY COMMISSION / Division of Technical Information

ONE
OF A SERIES ON
UNDERSTANDING THE ATOM

Nuclear energy
is playing a vital role
in the life of
every man, woman, and child
in the United States today.
In the years ahead
it will affect increasingly
all the peoples of the earth.
It is essential
that all Americans
gain an understanding
of this vital force if
they are to discharge thoughtfully
their responsibilities as citizens
and if they are to realize fully
the myriad benefits
that nuclear energy
offers them.

The United States
Atomic Energy Commission
provides this booklet
to help you achieve
such understanding.

Edward J. Brunenkant

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Director
Division of Technical Information

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Sources of Nuclear Fuel

By ARTHUR L. SINGLETON, Jr.

THE START OF A REVOLUTION

The year 1789 is remembered by students of history for three events that shook or shaped the world. One of these was the election of George Washington as the first President of the United States. A second was the now legendary mutiny on the HMS *Bounty*, a high seas rebellion led by Fletcher Christian against Captain William Bligh, celebrated in stories and motion pictures. A third— and probably the most significant —was the start of the French Revolution.

But another event took place that year, one which few recall and none celebrate, yet one that ranks high in worldwide significance.

This, too, was the start of a revolution, but no one knew it at the time. It was to be a quieter, nonetheless genuine, upheaval, for it opened the door to a completely new development in the world of science.

Uranium country on the Colorado Plateau. Unaweep Canyon leading south from Grand Junction, Colorado, to the Uravan mineral belt, some 50 miles away. The winding road on the canyon floor, known as "the uranium road", is used by truckers to bring ore from the mines.

This unsung incident occurred in the relatively obscure laboratory of a German scientist named Martin Heinrich Klaproth, who died without ever realizing its true significance. It was to him an accidental and passing discovery.

M. H. Klaproth

Klaproth was working on projects involving pitchblende* ores. In the course of his experiments he isolated from the ores a black powdery material with chemical properties strikingly different from those of any elements he knew. He was pleased and amazed at his find, but also curious.

He showed the substance to other scientists, and they, too, were baffled. No one could identify it nor see a use for it. But it was new and it needed a name, and in honor of the planet Uranus, which had been discovered a short time earlier, Klaproth called his puzzling material uranium.

For more than a century, this strange substance remained little more than a laboratory curiosity. Then, in 1896, the French scientist Henri Becquerel made a startling discovery while working with it.

He was studying phosphorescence, the capacity of some materials to glow in the dark after being exposed to strong light. At one point in his work, he casually and without purpose placed some uranium salts on paperwrapped photographic plates in a dark desk drawer. Several days later, he developed the plates, and found to his amazement that the plates had been darkened as if exposed to light.

He knew that the source of energy for such an exposure had to be the uranium salts for nothing else was in the drawer. Repeated trials proved it was no accident, and he exultantly proclaimed his find.

*For definitions of mineral names, and other terms, see the Glossary beginning on page 59.

MILESTONES OF NUCLEAR FUEL DEVELOPMENT

1789	Klaproth isolates uranium from pitchblende ores
1896	Becquerel discovers uranium's radioactivity
1898	Pierre and Marie Curie discover radium
1938	Hahn and Strassmann succeed in splitting uranium atom
1942	First nuclear chain reaction achieved at Chicago
1945	First successful test of atomic device near Alamogordo, New Mexico
1946	Congress establishes Atomic Energy Commission
1947	Great uranium rush in U. S. began. Boom came in 1951–1958
1951	First significant amount of electricity from atomic energy produced at Idaho reactor testing station
1954	First nuclear-powered submarine, the *Nautilus*, commissioned
1955	First United Nations International Conference on Peaceful Uses of Atomic Energy held in Geneva, Switzerland
1957	First commercial use of power from civilian reactor in California; International Atomic Energy Agency formally established
1959	First nuclear-powered merchant ship, NS *Savannah*, launched at Camden, New Jersey; first nuclear-powered Polaris missile submarine, *George Washington*, commissioned
1961	First use of nuclear power in space as radioisotope-operated electric generator is placed in orbit

Thus, Klaproth's mysterious uranium, which had failed to gain attention for 107 years, suddenly took on dazzling potential. It had the seemingly incredible ability to give off energy spontaneously, that is, without previously having been exposed to any other source of energy.

Several years later, Pierre and Marie Curie studied the properties of the element radium, which they had derived from similar pitchblende ore,* and named this phenomenon—also a property of radium—radioactivity. Men are still studying its astonishing facets.

Despite the amazement that greeted Becquerel's observation, 50 years passed before the next development of consequence occurred in connection with uranium.

As late as 1939, just before the outbreak of World War II, in a report given in New York City, a scientist observed that uranium had no economic significance except in color-

*The Curies shared a Nobel Prize with Becquerel for their work.

ing ceramics, where it had been proved valuable in creating various shades of yellow, orange, brown, or dark green.*

The paper was, of course, not representative of general scientific thought in 1939, but it does illustrate the extent to which many men had failed to recognize the potentialities of this radioactive element.

Knowledgeable scientists, in fact, already had begun exploring the nature of atoms by bombarding many elements with high-energy subatomic particles produced by several kinds of laboratory devices. It was natural that this should be tried with uranium, the heaviest known element. Late in 1938, the German experimenters Otto Hahn and Fritz Strassmann succeeded in splitting uranium atoms by exposing uranium to a stream of tiny atomic particles called neutrons. This produced some known but lighter elements we now call fission products because they are the pieces formed when the nucleus of a uranium atom splits in two, or fissions.†

Although the birth of the atomic age antedates this achievement, the Hahn-Strassmann experiment stands as a milestone in the development of atomic energy—the point at which the use of uranium began to gain momentum.

As news of the German discovery spread, other scientists began theorizing that the splitting of a uranium atom released not only energy but neutrons. And the possibility was widely discussed that neutrons from one fissioning uranium nucleus might be used to split other uranium nuclei, thus leading to a chain reaction that could release unlimited amounts of energy.

This theory soon was put to the test, and the first sustained nuclear chain reaction was achieved by the United States at the University of Chicago in 1942.‡ The atomic bomb was developed 3 years later by the Army's

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*Some uranium-colored pottery, for example, is radioactive enough so that it can be used as a source of radiation for simple home experiments.

†Fission is explained in more detail in *Our Atomic World,* a companion booklet in this series.

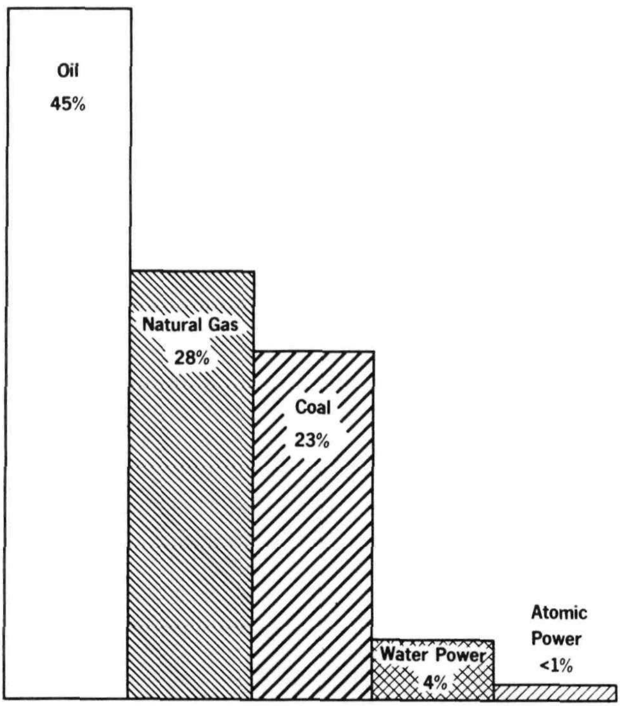
‡See *The First Reactor*, a companion booklet in this series, for a full account of this development.

Manhattan Engineer District, under what was known as the "Manhattan Project".

Although the military objective of achieving a weapon of unprecedented power took priority during this World War II period, scientists working on the project already were anticipating the day when the energy of this element could be harnessed in a controlled chain reaction and put to peaceful uses. If uranium fission were controlled on a practical basis, they reasoned, a new source of heat and light would become available, and the world's concern about having sufficient fuel in centuries to come would be considerably eased.

For centuries, men had relied on so-called "fossil fuels", such as coal and oil, first for heat, then to run their machines and to generate electrical power. But the supply of this type of fuel is not inexhaustible. The question was

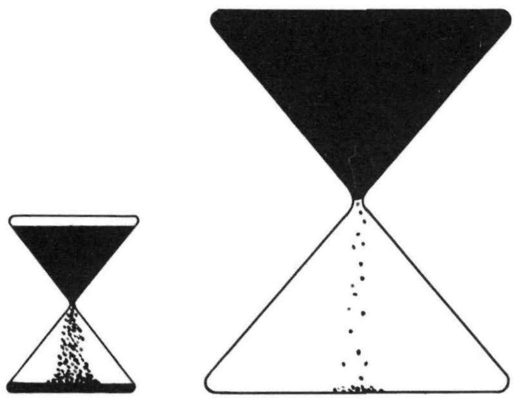
ENERGY PATTERNS TODAY



asked: What will keep the world going if it runs out of coal, oil, and natural gas?

The answer was at hand, but few people other than nuclear scientists realized this fact until a relatively short time ago. Many persons probably still think of uranium only as a very valuable material that is radioactive and essential to the production of atomic bombs. They are perhaps awed by the enormous might locked within its atoms, without appreciating how patient scientists and ingenious engineers, with the aid of modern technological advances, have worked to devise ways for releasing that power safely, surely, smoothly, and in whatever amounts are needed. Little is thought, usually, about uranium as a nuclear fuel, or of possible substitutes for uranium.

A WAY OF LOOKING AT OUR FUELS SITUATION



The only natural material directly suitable for nuclear fission is the isotope* of uranium, uranium-235. This comprises only about 0.7% of natural, or normal uranium — 7 parts in 1000. Another isotope, uranium-238, makes up almost all the remaining 99.3%, and this is not fissionable in the same sense as is ^{235}U.† Uranium-238, however, can be converted in a nuclear reactor into a useful fissionable

*Isotopes are differing forms of the same kind of atom, distinguishable by weight but alike in other respects. See Glossary.

†^{238}U is fissionable only by "fast" neutrons.

material—a plutonium isotope, plutonium-239. Plutonium is not a natural element, but is one of a series of man-made elements scientists have developed in their efforts to find new nuclear fuel sources, as well as for other purposes.*

Thorium is the only other natural nuclear fuel source of consequence. It is a heavy, slightly radioactive metal, discovered by Jöns Jacob Berzelius, a Swedish scientist, in 1829.

Thorium is not fissionable, as uranium-235 is, but is "fertile", like uranium-238, so it also can be converted in nuclear reactors into a fissionable isotope—in this case uranium-233 (which is *not* found in nature).

There has been little demand for thorium to date, and therefore, slight prospecting activity seeking its ores. But one important area of potential production in the United States has been found at Lemhi Pass, in Idaho and Montana.

Neither thorium nor uranium-238 can be converted, or transmuted, easily or rapidly to fissionable uranium-233 or plutonium-239. Most existing reactors can produce rather small amounts of fissionable material from these two sources. New types of reactors are, to be sure, being developed to increase the production of fissionable materials, but even in these improved devices, the efficiency of conversion is likely to be low.† When scientists and engineers perfect ways to do this economically, a tremendous new source of energy will be available. But for many years to come, we must depend on natural uranium with its tiny portion of ^{235}U to meet our nuclear fuel needs.

That is why scientists, when they talk about fissionable materials, most often mean uranium-235. That is also why this book on nuclear fuel sources is essentially a story of one source. Thorium and company are waiting in the wings; uranium still has center stage.

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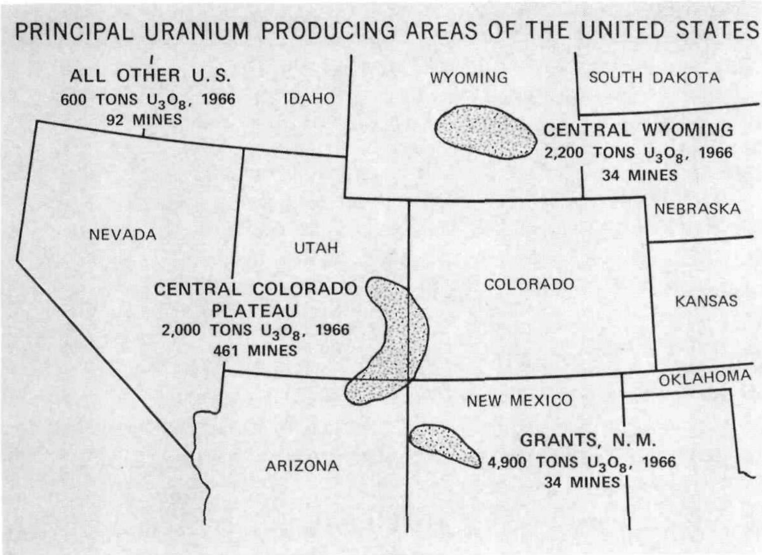
*For more about these elements, see *Plutonium* and *Synthetic Transuranium Elements*, other booklets in this series.

†These "breeder" and "converter" reactors are discussed on page 57.


PRINCIPAL URANIUM PRODUCING AREAS OF THE UNITED STATES
ALL OTHER U.S.
600 TONS U_3O_8, 1966
92 MINES
IDAHO
WYOMING
SOUTH DAKOTA
CENTRAL WYOMING
2,200 TONS U_3O_8, 1966
34 MINES
NEBRASKA
NEVADA
UTAH
COLORADO
KANSAS
CENTRAL COLORADO
PLATEAU
2,000 TONS U_3O_8, 1966
461 MINES
OKLAHOMA
NEW MEXICO
GRANTS, N. M.
4,900 TONS U_3O_8, 1966
34 MINES
ARIZONA

THE GREAT SEARCH

Before the start of World War II, American stocks of uranium were extremely low because there was little industrial demand for it. The United States, which had led the way in the application of nuclear fission, was dependent on foreign sources of supply. From mines deep in the Belgian Congo came much of the uranium needed for the development and production of the first atomic bombs. Every ounce of Congolese ore was hauled out through 1200 miles of rocky canyons and steaming jungles, then shipped across submarine-infested seas to the United States.

But the supply was just not enough and a widespread search for domestic sources was launched in the late 1940s. The Atomic Energy Commission offered a substantial bonus for discovery and delivery of new supplies, and soon an unorganized army of amateur and professional prospectors was swarming over western deserts and mountains, hoping for a uranium "strike". Thus began one of the most intensive metal hunts in history.

Dreams of riches spurred the searchers on. Uranium became a household word. The scene often was reminiscent in many respects of the gold rush days in California or Alaska, without the lawlessness, but with all the glitter and romance of overnight success, sudden wealth, and of the triumph, by a few lucky men, over wilderness, loneliness, and bad luck.

Grizzled old-time prospectors and trained geologists were among the searchers, but so were clerks, ranchers, teachers, students, businessmen, off-duty soldiers, and even housewives. Whole families sometimes "camped out" to search for the magic ore. More often the prospectors traveled alone, or in pairs, trudging into desolate rock deserts and remote mountain canyons. Some used burros, some drove pickup trucks or surplus Army jeeps as far as those vehicles would travel, and then clambered up the steep slopes and brilliantly colored sandstone cliffs on foot.

The exploration carried them into remote regions where panoramic vistas seldom seen by men stretched before their eyes. Most of the adventurers found little or no telltale radioactivity with their Geiger counters. Yet a

surprising number did locate important ore deposits, not infrequently in the abandoned workings of old radium mines, and later sold their interests to established mining companies.

A very few "struck it rich" and disposed of their rights for thousands or even millions of dollars.

Prospecting for uranium with hammer and Geiger counter.

Hundreds of claims were staked out. Hundreds of small tunnels were dug into mountainsides. Vertical shafts were sunk a few feet into scores of mesa tops. About a thousand small mines actually brought out marketable ore. When the rush at last subsided, about a score of mines, many of them by this time owned by large metal or chemical corporations, accounted for about 85% of the known ore reserves in the Colorado Plateau, where most of the great search was concentrated.

To understand this uranium rush of the late 1940s and early 1950s, one should understand more about uranium itself.

First of all, uranium is a metal, just as iron and gold are metals. The black powder Klaproth called uranium was not in a pure state, but in the form of an oxide. For comparison, you might think of iron ore, which consists of

oxides and other compounds of iron, but is not metallic iron.

Industry is able to produce pure metal from the oxide form, however, and in its freshly milled and polished state, metallic uranium has a silvery luster. However, like many metals, it oxidizes rapidly and soon becomes coated with a black layer of oxide by the action of air and moisture on the metal surface.

Uranium is heavy—one of the heaviest of all metals. It weighs about 65% more than lead. A piece as large as a soft-drink can weighs about 17 pounds.

Uranium is also radioactive, as we know, and this characteristic helps prospectors locate it in the earth. Using Geiger counters and other devices for detecting radioactivity, searchers can locate deposits of uranium ore that are not apparent by other means.

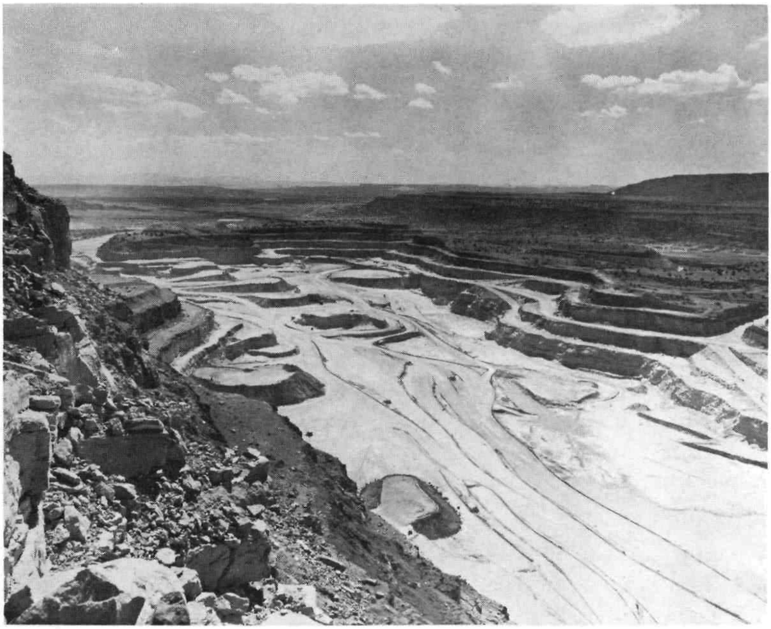
Early in the intensive period of seeking uranium, only a few really good sources were known. These were the known pitchblende ore deposits at Shinkolobwe in the Belgian Congo, Great Bear Lake in the Northwest Territories of Canada, and the Joachimsthal area* in Czechoslovakia. Prospectors knew about, but had little concept of the extent or richness of what appeared to be unique carnotite† deposits in a vast and rugged mountain-and-desert land, the Colorado Plateau in the American West.

But as uranium became a prime target for prospectors, new sources turned up. In South Africa, for example, tailings remaining from treatment of the high-grade gold ores were reprocessed for uranium. In 1949, only 3 years after the Atomic Energy Commission was established, uranium ore was found in the Todilto limestone near Grants, New Mexico. In that same year, the Happy Jack copper deposits in Utah were first mined for uranium, although uranium had been known there since 1920. And in 1952, geologists of the Anaconda Mining Company discovered the outcrop that became the now-famous Jackpile Mine in New Mexico. This

*Our word "dollar", it is interesting to note, is derived from the name of an Austrian coin, the "thaler", made of Joachimsthaler silver, that is, silver from Joachimsthal.

†Carnotite is a uranium-bearing ore.

mine has since produced millions of tons of primary black uraninite and coffinite ore, rich in usable uranium.



The Jackpile Mine in New Mexico is the largest open-pit uranium mine in the United States.

Within 3 more years, many additional ore deposits had been discovered— in the Black Hills of South Dakota, in the Gas Hills of Wyoming, and in Utah, where the famous Mi Vida and Delta Mines made millionaires out of prospectors. Canada, France, Australia, and Argentina also reported discoveries.

The search for uranium continues today as exciting new uses are in prospect. The full extent of our capability to produce uranium from the earth's depths is not known. But history is on the side of those who continue the search, for the story of civilization is, in part, the story of a successful quest for fuel.

Man always has been able to find a new fuel long before his supply of old fuel has been consumed, and well before there has been either a demand for it or a technology for using it. Petroleum, for example, was hardly more than a

lamp fuel and a minor lubricating material, until it became needed to run gasoline engines and brought the machine age into flower.

Uranium has been known for more than a century, but only in our day is beginning to come into its own as a source of power for the world.

Sources of uranium are essentially unlimited, but it will take a great deal of ingenuity to make use of these supplies so that they will be available long after the fossil fuels are gone.

For example, a cubic inch of uranium metal has the energy potential of about 20,000 cubic feet of coal, 17,000 cubic feet of oil, or 20 million cubic feet of natural gas. With this in mind, consider that there are hundreds of thousands of tons of uranium readily available, and that scientists are now developing ways of utilizing this energy potential to its maximum. Such a supply, even if it is used up at a much faster rate than we now envision, can keep us going for centuries.

This is not just the hope, but the firm conviction of geologists who still search the world for traces, however faint, of Klaproth's metal.

ENERGY COMPARISONS

The nuclear energy released from 1 pound of plutonium is equivalent to the chemical energy that can be obtained from 3,000,000 pounds of coal (enough to fill 25 railroad cars).

PETRIFIED RIVERS

Uranium makes up about two parts per million (ppm) of the earth's crust, and traces of it are found almost everywhere. Its abundance is greater than that of gold, silver, or mercury, about the same as tin, and slightly less than cobalt, lead, or molybdenum. There is an average of 1 pound of uranium in every 500,000 pounds of the earth's rocks. (Thorium, making up an estimated 12 parts per million of the earth's crust, is 6 times as plentiful.)

Uranium is much more abundant in rock formations than in water or petroleum. In high-silica igneous rocks, such as granite, for example, the element comprises about 4 parts per million.* In ocean water, its concentration is only about 2 parts per *billion*, and in ground and stream water the usual concentration is even less.

Uranium, like most other metallic elements, does not occur in nature as a free metal. It is always found combined chemically with oxygen and other elements, and usually it occurs in the form of uranium oxide (the mineral uraninite, which is also known as pitchblende), uranium hydrous silicate (the mineral coffinite), and potassium uranium vanadate (the mineral carnotite).

The widespread distribution of uranium in rocks is attributable to its chemical and physical properties. In nature, uranium has two valence states, which give it greater chemical capacity to react under different environmental conditions. It forms both relatively soluble and insoluble compounds thus enhancing its ability to be transported and accumulated from natural waters into ore deposits.

Uranium readily forms compounds with a large number of other natural elements, enters the structures of many minerals, and takes part in a variety of chemical reactions. Thus it has become distributed over the ages in a variety of rocks and mineral deposits. Although uranium is found in many rocks, it is not often found in large ore bodies such

*This is why natural, or background, radioactivity is slightly greater on a city street flanked by granite-front skyscrapers than in many other human habitats.

as those formed by other metals of similar abundance. Its most interesting occurrence, from both a geologic and an economic standpoint, is in the sedimentary rock formations of the western United States.

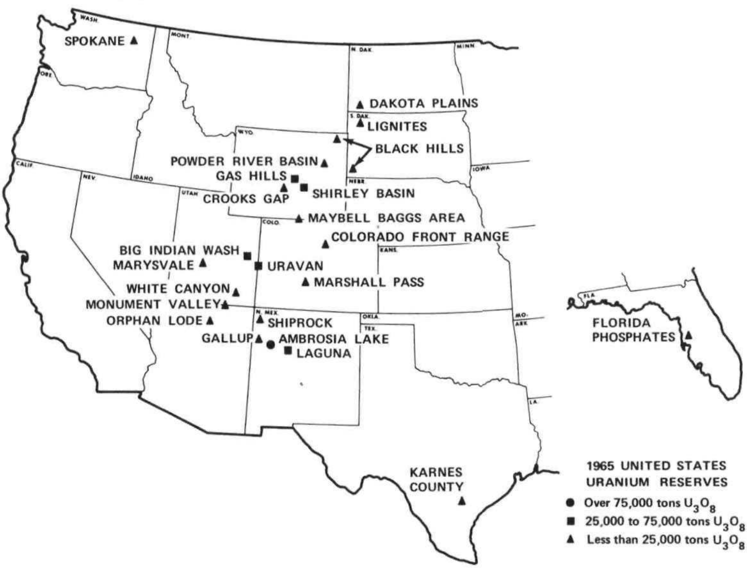
A prospector or miner following a uranium discovery in the western United States often finds visible indications of the metal's ancient past. A petrified log 200 million years old may be encrusted with uranium. Ripples worn by long-vanished inland seas may be seen in sandstone beds that have been raised thousands of feet above sea level in one of the most arid portions of North America. The fossil remains of dinosaurs, prehistoric crustaceans, and ancient trees are common in this vast wasteland.

Dinosaur tracks in Navajo Canyon, Arizona, arouse the professional interest of this geologist.

About 95% of the uranium ore mined in the United States is found in pitchblende and coffinite deposits. These were buried many millions of years ago in sandstones formed by rushing streams in what was once a gigantic semitropical savannah teeming with turtles and crocodiles. At some point in geologic history, ground waters carried dissolved uranium into these ancient stream channels where the

chemicals produced by decaying plants could precipitate it. The chemical encounter between the water-soluble uranium and the organic products resulted in the formation of literally thousands of ore bodies containing pitchblende, coffinite, carnotite, and many other uranium minerals. Today, geologists look upon these deposits as having been formed in "petrified rivers" since much of the original plant material buried in them has been changed to mineral or stone.

IMPORTANT URANIUM DISTRICTS OF THE UNITED STATES



There are many interesting facets to these ancient river deposits of uranium. For example, in the eastern part of the Colorado Plateau, which includes much of western Colorado, uranium is associated principally with vanadium to form carnotite. In the western Colorado Plateau, which includes much of eastern Utah, uranium is associated with copper. In the Wyoming basins, prospectors have found uranium with phosphate, arsenate, selenium, and molybdenum. In Texas and North Dakota, arsenic and molybdenum are abundant. Geologists have concluded from this that

many kinds of metals and other elements have been transported and have accumulated with the uranium. Rhenium, a rare metal that has many important uses in the electronic industry, also occurs in these deposits, but it has not yet been found in quantities that can be mined or recovered economically.

How these deposits were formed has long been a puzzle to geologists seeking to unravel the secrets of the ore's whereabouts. Many feel that tiny microbes, with special food requirements, created chemical sinks containing hydrogen sulfide that precipitated the uranium and other metals as they were introduced into the sands by ground waters. They surmise that the ore deposits are not static, that they will not always remain where they are, for the ore is still subject to the chemical reactions of ground waters that continually leach away and redeposit the uranium. This may happen again and again, until all of the river-laid organic material is destroyed and nothing is left in the sandstone to precipitate the uranium. Fortunately for us, it would take millions of years to destroy the existing ore deposits. However, geologists must continually appraise new prospecting areas in terms of the ravages wrought by these destructive processes during past geologic time. Many rocks that might contain uranium, but do not, are known to have been chemically altered in this manner.

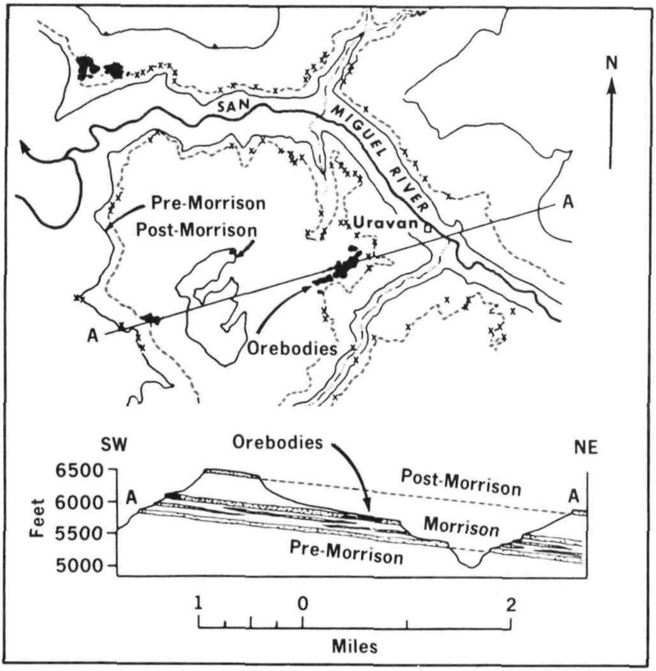
It takes training and a great deal of experience to evaluate rocks and the clues they may provide to the existence or absence of uranium.

The area of the uranium-bearing "petrified rivers" is a broad, arid territory marked by white, gray, vermillion, and beige cliffs, enormous rock gorges, flat-topped mesas, steep rocky slopes, and seemingly endless hot dry plains. The area encompasses the central and southern parts of the Colorado Plateau, the Wyoming basins, and the flanks of the Black Hills.

The Colorado Plateau covers parts of Colorado, Utah, Arizona, and New Mexico, an area of about 14,000 square miles spreading out on all sides from the Four Corners—the only place where four states come together at one common point. Uranium deposits in this vast region constitute the principal domestic source of the metal. First

mined for radium* just before the turn of the 20th Century, the area was next probed for vanadium with considerable success, and finally for uranium.

Nearly horizontal beds of eroded, sedimentary rocks that once were the bottoms of Paleozoic Era oceans stretch for miles high above the winding present-day valleys. This is "rim-rock country", a region of "wide-open spaces", a land of ancient man's cliff-dwellings and modern man's national monuments.



Map and related cross section of the geological formations in the Uravan area of the Colorado Plateau, showing where orebodies have been found. "Post-Morrison", "Morrison", and "Pre-Morrison" are successively lower layers of sandstone; the Morrison strata contain carnotite deposits.

The second largest region of uranium deposits is in the so-called Wyoming basins of central and northeastern

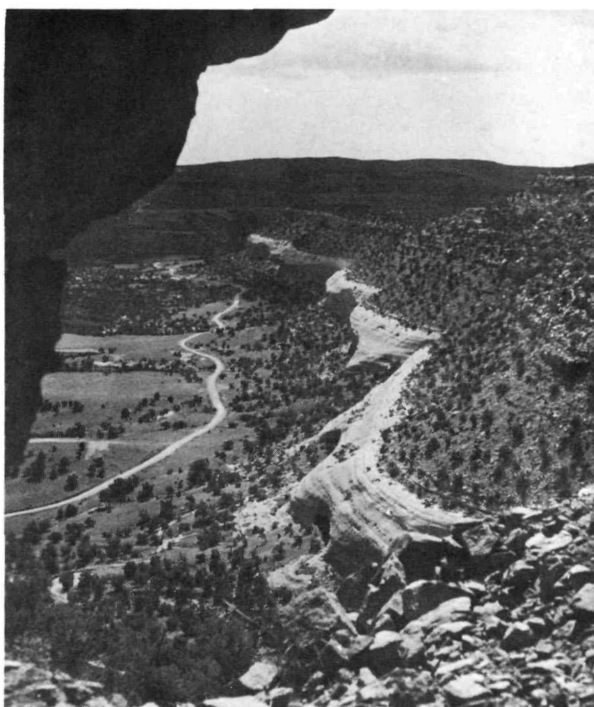
*Some of the radium ore used by the Curies came from the Colorado Plateau. It was a gift to them from the people of the United States.

THE COLORADO PLATEAU

Wyoming. Carnotite ores were discovered here in 1951, but most production is now from pitchblende and coffinite.

All but about 10% of U. S. uranium production has been from these two areas, but smaller districts, showing promise of greater productivity in the future, have been found in or near the Black Hills in South Dakota and Wyoming; at Tallahassee Creek in Fremont County, Colorado; and in the Texas Gulf coastal plain.

It should be kept in mind, however, that while many deposits have been uncovered in these regions, many parts of these uranium belts have yet to be explored. Moreover, the uranium geology is still not completely understood. New understanding is being acquired through geologic research.



This view from the portal of an abandoned uranium mine in the Colorado Plateau looks out on horizontal layers of sandstone with "slick rock" formation predominating. In this area uranium is usually found in the Salt Wash sandstone above the "slick rock".

NATURE'S STOREHOUSES

Areas where substantial deposits are found are called uranium districts. Considering the geochemical behavior of uranium, scientists recognize at least three general factors that determine the geology of a uranium district.

(1) The nature of the rocks in which the ore has been deposited.

(2) The sedimentary (rock) or structural (fracture) framework through which the solutions moved.

(3) The nature of the original mineralizing solutions. Many kinds of solutions, ranging from magmas to rainwater, containing a variety of metallic and nonmetallic elements, may carry uranium through rocks.

Types of Deposits

There are three important types of uranium deposits. The "sandstone-type" deposit, in which the ore trends horizontally or nearly so and is confined to a particular sandstone bed, or "petrified river", has already been described. The second is known as the "vein-type" or simply "vein" deposit. Veins tend to be vertical or rather steeply inclined and cut across sedimentary, igneous, and metamorphic rock formations. They are formed in fractures through which solutions either moved up from great depth or down from the surface. Most veins of uranium probably were formed from heated solutions that were squeezed upward into fractures under great pressure.

Occasionally, uranium also occurs in veins with more exotic elements, such as columbium, tantalum, and titanium, in minerals known as uranium multiple oxides. Davidite, a uranium titanate, has been mined in Australia from metamorphic rocks. The multiple oxides are resistant to weathering and often accumulate in stream beds known as "placer type" deposits. Among these an unusual multiple oxide called euxenite has been mined for uranium in Idaho stream sands. It is believed that the euxenite was weathered out of igneous rocks far upstream and concentrated in the sands by the action of the rushing waters, in the same manner that gold nuggets are deposited in streams. Al-

though occurrences of multiple oxides of uranium are common, particularly in pegmatite deposits, more often than not too little of these minerals is present for profitable mining.

The third type of deposit, which is the most important occurrence outside the United States, is the "ancient conglomerate" type. In this, the uranium usually occurs as pitchblende in small grains in very old stream channels, formed more than a half million years ago. The huge deposits of the Blind River district in Canada and of the Witwatersrand in the Republic of South Africa are of this type. Geologists, even after years of study, still disagree on the origin of these deposits. In some respects the deposits are similar to "sandstone-type" deposits and in other respects to the "euxenite placer-type" deposits of Idaho, but there are also many differences.

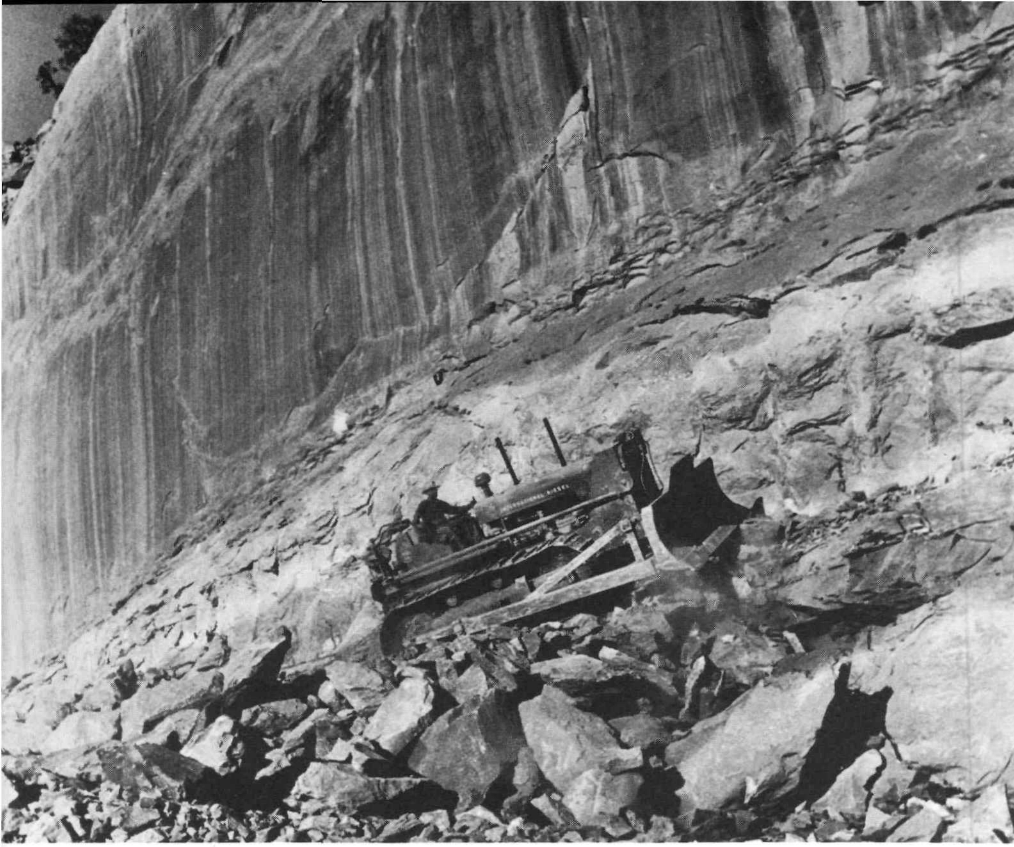
Locations of Deposits

Besides the Colorado Plateau and the Wyoming basins, other U. S. uranium districts include vein-type deposits from which about 5% of the uranium is mined in this country. The most productive of these are near Denver and Gunnison, Colorado, Marysvale, Utah, and Spokane, Washington.

In Canada, the Blind River district along the north shore of Lake Huron, in Ontario, is now the chief uranium source. At one time, only the Great Bear Lake and Beaverlodge districts exceeded it in importance. The Eldorado Mine at Great Bear Lake was the first important uranium mine in Canada and was an important source for the United States during World War II. The Bancroft district in eastern Ontario has also produced significant quantities.

In the Republic of South Africa, uranium is a by-product of gold production from the Witwatersrand conglomerates in the renowned gold-producing area known as the Rand. In the Belgian Congo, the famous Shinkolobwe mine was an appreciable contributor to the world's uranium supply until the late 1950s. This district produced some of the richest uranium ore the world has ever seen and yielded many fine specimens of uranium minerals.

SIGNIFICANT URANIUM OCCURRENCES IN THE WORLD



A bulldozer digs out an access road in Colorado uranium country.

In Australia, uranium has been produced in the Northern Territory, South Australia, and western Queensland.

The deposits of the central mountain region and the mountains of Brittany have contributed appreciably to the uranium stockpiles of France.

The uranium deposits of Portugal were discovered about 1907. As in France, the deposits are in granitic rocks. Pitchblende deposits have also been uncovered in the Sierra Morena region of south-central Spain and along the Portuguese border.

Uranium has been known in Argentina since the 1930s, but producing mines were not developed until 1952 when the National Commission of Atomic Energy was formed.

Sweden's alum shales are a vast, but relatively low-grade source of uranium, with notable occurrences in the Billingen-Falbygden, Vastergotland, and Narke provinces.

Uranium Formation "Provinces"

Formations that contain uranium ores are varied as to composition and age. They include sedimentary, igneous, and metamorphic rocks, ranging from a few million years to a billion or more years old. Although uranium deposits are widely scattered throughout the world, collectively they appear to be concentrated in five major tectonic or structural "Provinces": (1) The mountain axis (cordillera) extending the length of the North and South American continents from Alaska to Argentina; (2) The edge of the Canadian Shield; (3) The borders of the African Shield; (4) The region of small granitic mountain massifs extending from southern Europe into North Africa; and (5) An area of granite intrusives in eastern Australia.

Since only a small part of the earth's crust has been thoroughly explored, undoubtedly many more uranium ore deposits remain to be found to satisfy man's requirements for this amazing fuel.

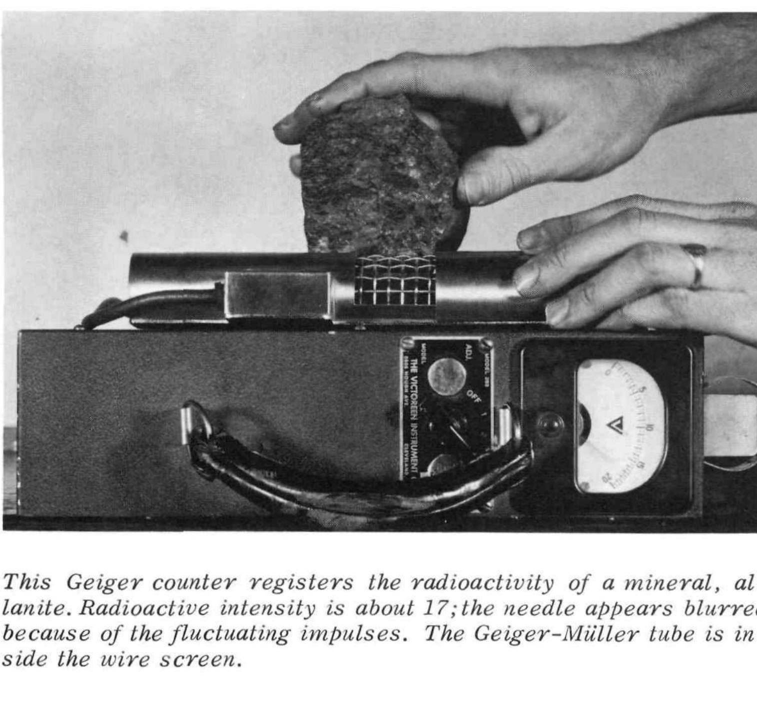
WITH JEEP AND GEIGER COUNTER

Uranium has been discovered in the United States mainly in veins and in flat, irregular, tabular, sandstone bodies. The deposits range in thickness from a few feet to perhaps 100 feet, at most, and in depth from surface outcroppings to about 2000 feet below ground.

Each type of rock formation can be explored and mined in various ways, but some general principles and practices apply in most cases.

The unusual property of uranium, its radioactivity, is helpful to prospectors. The rays and particles emitted by uranium can easily be detected with proper instruments even at considerable distances. This has made it possible to explore for uranium ore bodies by airplane and automobile, as well as on foot.

The most widely used detector, the Geiger counter, has as its "heart" the Geiger-Müller tube that consists of a thin metal shell with an insulated wire running lengthwise along the shell axis. The shell contains a gas, such as helium. A



This Geiger counter registers the radioactivity of a mineral, allanite. Radioactive intensity is about 17; the needle appears blurred because of the fluctuating impulses. The Geiger-Müller tube is inside the wire screen.

strong positive electrical charge is applied to the center wire, creating a high voltage between it and the shell. When beta or gamma rays given off nearby penetrate the tube, the gas is ionized, and electricity flows through it from center wire to shell. This current is recorded on a meter, indicated by light flashes or a clicking on headphones. There are many possible arrangements of the tube and its circuits, and the counter comes in various sizes — small enough to be carried by hand or large enough to require mounting in a vehicle or an aircraft.

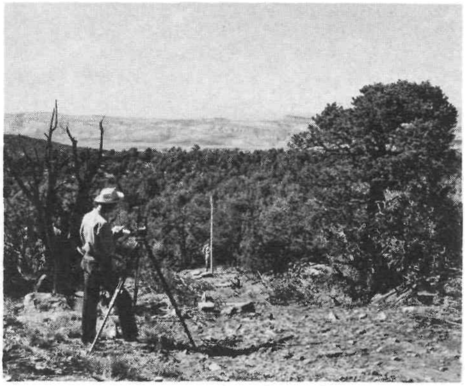
Another detection instrument is the scintillation counter, which depends in operation on the ability of gamma and beta rays to produce tiny, momentary flashes of light (scintillations) in specially prepared crystals of compounds, such as sodium iodide or potassium iodide.

An advantage of the scintillation counter is that it responds to a larger proportion of the rays penetrating the crystal. In other words, it is more sensitive and therefore superior for aerial and surface prospecting. The same quality, however, makes it less desirable for mine prospecting, because the radiation level underground ordinarily is much higher and it is harder to find which direction the radioactivity is coming from. And also, a scintillation counter costs three to five times as much as a Geiger counter.

A well-planned exploration program, which would employ either or both types of counters, would consist of three principal phases: preliminary reconnaissance, detailed geologic studies, and physical exploration.

A sound first step would be a thorough examination of all available written reports on the area under consideration. These would include information on rock formations and geologic structures. A stereoscopic study of aerial photographs, which often can be obtained from government agencies, also is a valuable preliminary.

Where aerial photographs are not available, many prospectors fly over an area to make their own observations and preliminary radiation surveys. Searchers have found that if the terrain is broad and flat, fast multi-engine aircraft can be used for the radiometric examination, flying at about 500 feet above the surface. For rough, steep



A mining engineer makes a preliminary survey prior to staking a uranium claim.

terrain, single-engine planes flying 50 to 100 feet high, at speeds of about 60 miles per hour, are effective.

Any discovery of radioactivity—whether made from the air, from a truck, or by a man on foot—is usually followed by surface, or ground, reconnaissance to locate the exact spot and determine the extent of the "hot" area.

First, the prospector must "stake his claim" if the discovery is on public domain, or lease the ground if it is privately owned. To stake a claim he must survey his site. Then he must make a "discovery cut"—a definite excavation—and drive marker posts in the corners of the claimed area, which cannot exceed 600 by 1500 feet in extent. A notice must be posted on the claim center line proclaiming the discoverer's rights to the minerals buried below. Finally a record of the claim and its location must be filed

A prospector posts notice, which indicates claim boundaries and ownership. "Brazil" is the name of the claim.

with the county clerk. In some states filing a map of the claim at the court house can substitute for the discovery cut.

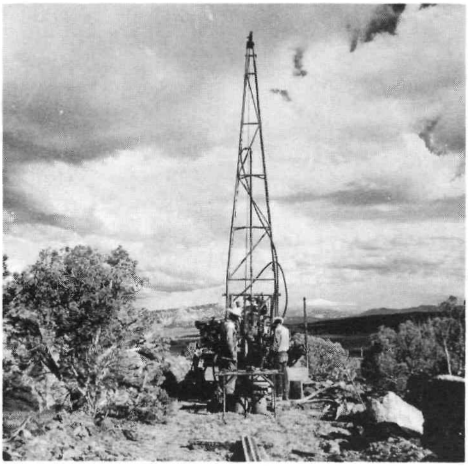
Even when the prospector has registered his claim he isn't sure there is enough uranium there to make mining it worthwhile. But if he has had favorable indications from his reconnaissance to this point, he is ready to begin the second phase of exploration: detailed geologic studies. These include surface mapping, sample taking, and the preparation of subsurface maps by projecting data that have been obtained from careful examination of the surface and exploratory penetrations of the ground.

The value of a deposit is determined by taking samples at enough points to reflect the size and grade of the deposit. Exploratory penetrations are made by boring small drill holes or by excavating underground workings big enough for men and equipment to enter. Trenching can be done with pick and shovel, or, on a larger scale, with a bulldozer. Mine openings, the most costly type of exploration, yield maximum information. They are made by the usual processes of drilling, blasting, and removing rock.

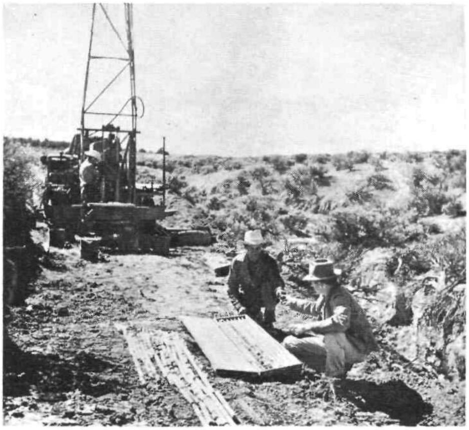
The most often-used types of drilling are done with core, rotary, pneumatic percussion, and churn drills. Core drilling is most expensive, but often is most informative. Rotary drills, first developed for seismic exploration, are widely used for uranium exploration, particularly in sedimentary rock.

The drilling procedure used in exploration depends on the countryside. For example, in the large sandstone deposits of Wyoming, found generally at depths of perhaps 200 feet, sample drilling can be closely spaced at low cost. But not so in the Grants, New Mexico, area where deposits representing millions of tons of ore are buried from 500 to more than 1500 feet. Drilling is more expensive here.

A third phase, mine development, may or may not be warranted by findings of the first two types of exploration. The topography, elevation, climate, availability of water, and the general geologic situation must be considered in determining the kind and extent of the effort to be expended. Obviously, costs must be weighed against the evidence of possible returns. Then the physical exploration may be



A drilling rig at work.



Cores recovered by diamond drilling are examined by geologists for traces of uranium.

accomplished through trenching, stripping, making actual mine openings, or drilling more extensively.

Large ore bodies of the future probably will be found at much greater depths than those located previously, geologists believe. Penetrations may run to 5000 feet, for example, making drilling much more costly. So far, as each new ore district has been worked, the economical drilling limit has been extended—that is, the value of the deposit has justified the expense of the deeper exploration.

At 5000 feet, much future drilling may be done with oil-well equipment, using drills 8 to 9 inches in diameter,

at an approximate cost of $5 a foot. At lesser depths, of course, slimmer holes are feasible and drilling costs drop.

The employment of rotary oil-well drills adapted for uranium mining already has been of considerable significance. Engineers claim that as use of these rigs increases the cost of drilling will decrease.

Exploring for uranium obviously is a complicated business, requiring considerable outlays of time, talent and money. The next step—mining—in finding and using this primary nuclear fuel source is no less complex and costly.

POWER SHOVELS AND BLASTING POWDER

Uranium ore is recovered from the earth by typical mining methods in much the same way other minerals are retrieved. There are, however, variations to fit the unusual characteristics of deposits in sandstone, from which about 95% of our domestic uranium is derived.

For shallow deposits, open-pit mining is common. For greater depths, underground mining techniques are general. During most mining, the grade of ore is ordinarily determined by radiometry—a method usually consisting of a man using a Geiger counter. Radiometry must be supported by chemical analysis, however, since a Geiger counter records only beta and gamma radiations, which are not emitted by uranium, but by radioactive elements resulting from uranium disintegration.*

Although open-pit mining is simplest, safest, and most efficient, this operation requires the stripping off of all the often enormous rock quantities overlying the deposit. Open-pit mines are sharply limited in the depth to which

*See *Nuclear Clocks*, another booklet in this series for an explanation of radioactive decay chains.

A welder repairs a power shovel dipper on the floor of an open-pit mine.

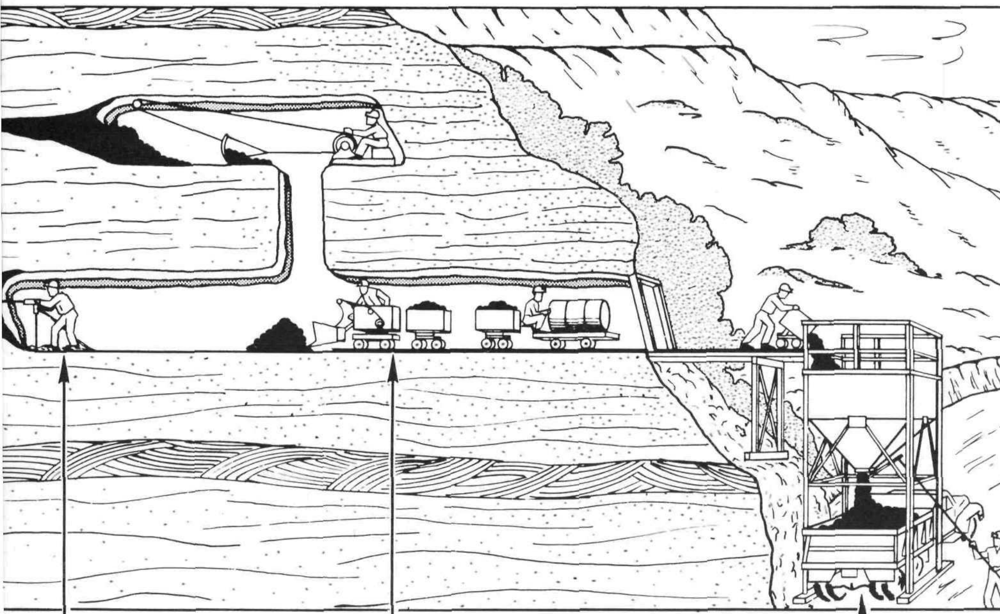
they can go, because pit slopes usually must be at less than 45° angles to prevent cave-ins.

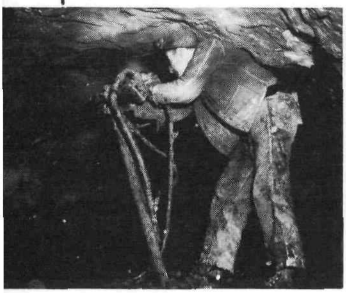
A typical open-pit mine resembles a section of an inverted cone projecting upward from the ore body. The maximum depth of open-pit uranium mines is about 300 feet. Costs run from \$5 to \$15 per ton of ore mined.

From above, an open-pit mine looks something like a huge futuristic city left over from a Hollywood movie set. Dozens of giant power shovels may be gnawing into the dusty earth as one level after another descends, seemingly without end. Heavy trucks loaded with rock have the appearance of crawling ants along the terraced roadways. The men and equipment in the deepest sections or directly across the diameter of the pit-mouth also seem to be tiny, much as pedestrians on a city street seem unreal and strange when we look down on them from a tall building. An open-pit mine moves huge quantities of rock and earth each day. It's an impressive sight, not easily forgotten.

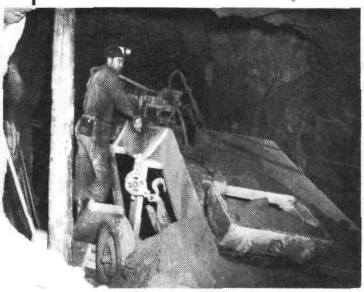
Deeper deposits must be extracted by underground operations, which cost from \$5 to \$30 per ton mined. Balancing

Looking down into an open-pit mine in Wyoming.

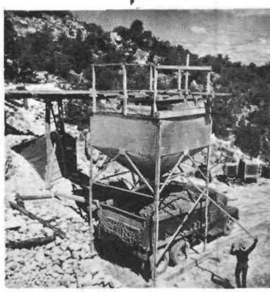




Drilling blast holes
with a jack-leg drill.



Scraping ore
into mine car.



Mined ore is dumped into
a truck from a hopper.

the higher cost, however, is the fact that only a relatively small amount of waste rock need be handled or removed.

Nevertheless, underground mining often requires the miners to drill and blast their way through many tons of rock to reach the ore. Tunnels must be dug horizontally or shafts sunk vertically. Working galleries and other spaces must be hollowed out of solid rock. Heavy timbers often must be placed to support the roof. Cross-cut passages at right angles to the main tunnels, vertical "raises"

or "inclines", and other spaces must be opened to bring the men to the ore body and provide space for machinery.

In small workings, miners rely on picks and shovels, air compressors, jack-hammers, and small jack-leg drills. Holes are drilled into the rock face, charges of explosive are carefully placed in them and detonated, and when the rock and dust have settled, the broken material is hauled out in wheelbarrows or small dump cars. In larger mines, workers may use diesel loading and hauling equipment. Ventilating equipment, power lines, and drainage pumps and pipes may have to be installed. Some mines have electric lights, but hard-rock miners underground often wear head lamps on their protective helmets.

Uranium miners often employ a room-and-pillar technique when they reach ore. This allows the workings to be confined to the ore body. They hollow out a rectangular pattern of "rooms", leaving pillars of ore in place to support the roof. During final phases of mining that area, the pillars are removed in turn and the roof is allowed to cave in. Stopes, steplike workings to remove ore, are always confined to the ore body if possible, since removal of waste rock dilutes the value of the ore.

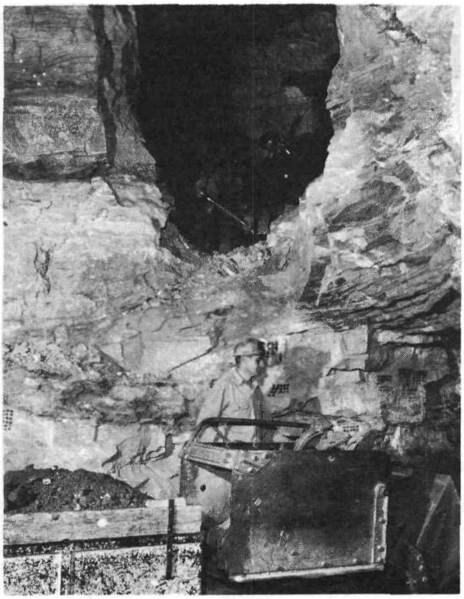
Most uranium ore bodies are long but not thick, and this configuration requires special adaptations of routine mining methods, as well as the development of new ones. Coal mining technology is not directly applicable, for example, because uranium bodies, although similar in their flat-lying

Ore pillars support a mine roof.

attitude to coal bodies, are harder, smaller, and more irregular.

Because the uranium at any one site is often quickly mined out, both developmental and mining operations must be highly mobile, designed to permit an inexpensive and rapid conclusion of digging. Improved shaft-sinking and rock-cutting methods have emerged. Old drill holes from the surface have been enlarged for ventilation and to admit water pipes, power lines, and other equipment. Sometimes men and ore are hoisted through such enlarged holes. Rubber-tired, mobile excavating and hauling equipment is employed wherever possible. Vast networks of wire safety netting are anchored to the rock overhead with roof bolts, in an improved and cheaper fashion than was formerly possible.

Even with the special adaptations found necessary, uranium mining is similar enough to other mining methods to have benefitted from progress in general mining technology. Less expensive rock-breaking explosives and techniques have been brought into use, and within the next few decades atomic explosives may be employed. When this is possible, entire ore bodies of great size can be broken up at once



Loading ore in an underground mine.

with a minimum of preparatory work, thus reducing costs drastically.*

Two rather recent developments have been hailed as of major significance to the future of the uranium mining industry. The first began with a decision in 1963 by the Jersey Central Power and Light Company to build a nuclear electric generating plant with a minimum capacity of 515 megawatts at Oyster Creek, New Jersey. This plant was the first of many large nuclear plants that have since been ordered, which, together with others expected in the future, will greatly expand America's nuclear power supplies. By 1980, it has been estimated, uranium-fueled reactors will provide an estimated 150 million kilowatts of generating capacity.†

The second was an amendment by Congress of the Atomic Energy Act to permit private ownership of fissionable materials, and to provide for toll enrichment by the Atomic Energy Commission of privately owned natural uranium—that is, permitting the AEC to turn natural uranium into reactor fuel for private industry for a service charge, or toll.

The Atomic Energy Commission has pointed out that although toll enriching will not begin until 1969, uranium producers probably can anticipate a market for additional uranium beginning earlier than that date.

These developments give promise of an earlier and greater demand for uranium than had been expected.

No matter what changes these will bring in the mining of uranium, however, use of the material still depends on a combination of the additional steps of milling and refining before it is put to its ultimate use, the production of nuclear energy.

*For a full discussion of peaceful uses of nuclear explosives, see *Plowshare*, another booklet in this series.

†This compares with 7 million kilowatts of nuclear generating capacity, and a total U. S. capacity of about 250 million kilowatts, in 1966.

CRUSHERS AND CHEMICALS

Milling

Uranium ore, typically containing about 5 pounds of uranium* per ton, is processed in steps. First, the raw ore is crushed, then ground finer, and leached (by percolating chemicals through it) to dissolve uranium minerals from the rock in which they were found. Next, the uranium-bearing solution that results from the leaching is separated from the undissolved material, and finally, the uranium is recovered as a chemically precipitated concentrate.

Uranium ores are rarely concentrated by the flotation or gravity procedures that commonly are used in dressing other ores. Usually all the ground uranium ore is subjected to the action of dissolving chemicals.

A typical uranium processing mill is a complex of industrial buildings, often including several that seem to "leap-frog" down a mountainside. Huge receiving bins are loaded at the top, and as the ore passes through successive heavy crushing machinery and screening operations, it is carried by gravity and by conveyors down the hill through stages of chemical treatment. It is commonly re-elevated by conveyors between stages.

Despite the use of heavy equipment moving hundreds of tons of ore a day, the process is a precise one, carefully controlled to extract every bit of the precious uranium from the various precipitates and solutions.

Both diluted acids and alkaline carbonates are used in "milling", the ore-processing operation. Acids work faster but are not as selective, with the result that many other elements are dissolved along with the uranium, thus complicating the subsequent purifying operations. Alkaline carbonate solutions are slower but more selective, thus simplifying purification. Uranium sometimes is precipitated directly from alkaline solutions.

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*Uranium concentration in raw materials is customarily expressed in terms of "black oxide", or U_3O_8, content. To obtain the actual uranium content, multiply figures given on this basis by 0.85.

Uranium mill at Uravan, Colorado.

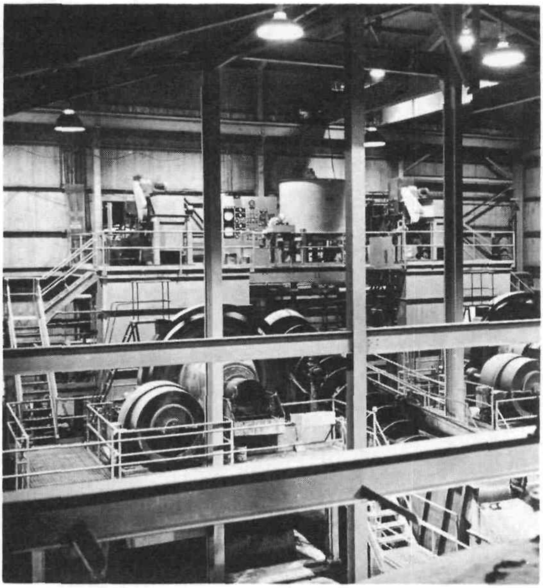
Uranium is separated from other substances in the leaching solution by one of two well-known chemical processes: *ion exchange* or *solvent extraction.* Both processes concentrate the uranium in a refined solution from which it is precipitated in the form of a pure compound.

Ion exchange utilizes a property of certain organic resin beads to remove uranium ions from either acid or alkaline leach solutions. In the process, an ionic component of the resin is exchanged for an ionic portion of the solution in which the resin is immersed.* In this process, virtually all uranium in solution can be transferred to the resin.

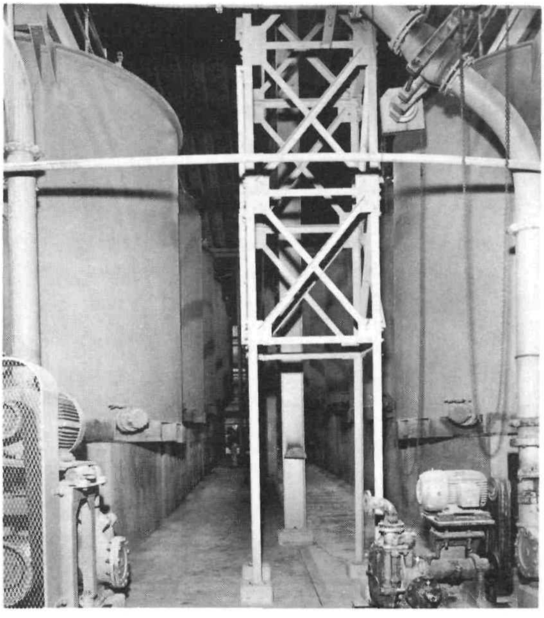
Solvent extraction is a similar chemical process. In this, an organic liquid solvent, with a selective affinity for uranium, is thoroughly mixed by agitation with an acid leaching water solution of impure uranium. The uranium is extracted from the leaching solution into the solvent, in which it is more soluble, leaving the impurities still dissolved in the

*A home water-softener is a familiar example of ion exchange processing.

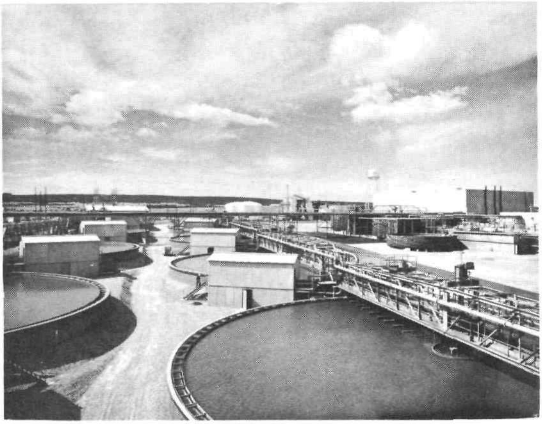
water. When the stirring process is stopped, the water and the solvent separate into two layers that are readily segregated.



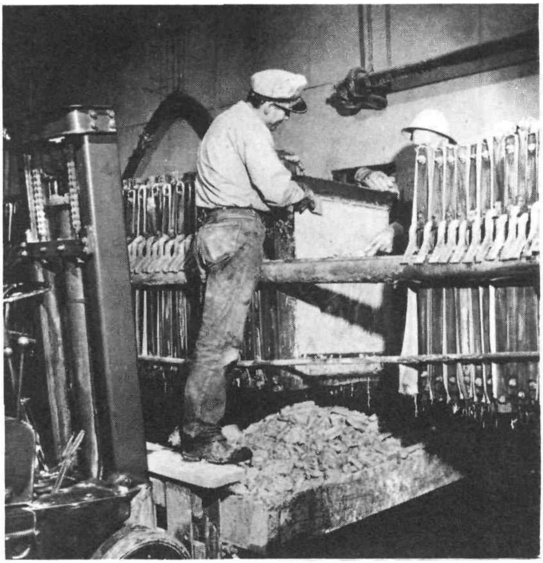
Machinery for pulverizing ore.



Acid leach tanks.



Thickener tanks in which suspended uranium settles to the bottom.



Mill workers removing "yellow cake" from a filter press to be dried, packed in steel drums, and shipped to the Atomic Energy Commission.

Processes now used in the domestic uranium milling industry can recover as much as 95% of the uranium content. Concentrates in the form of uranium oxides,* containing 75 to 98% uranium, are shipped from the mills to central refineries where still more highly purified products are turned out.

Some uranium minerals, including oxides of uranium with columbium, tantalum, and titanium, and those containing

*In a powdery solid, known as "yellow cake".

lime or sulfides, do not lend themselves readily to extraction and usually are not accepted as mill "feed". Thorium, molybdenum, zirconium, vanadium, and fluorine are difficult to exclude from the uranium product, and therefore the presence of large amounts of these materials in uranium ores makes the ores undesirable for milling.

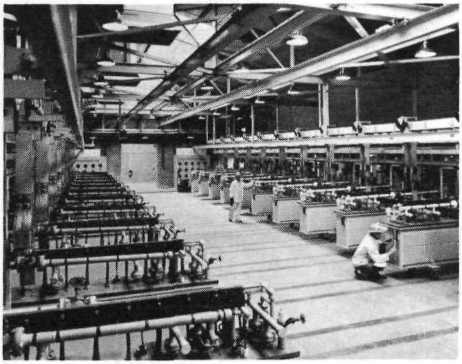
There were 16 milling facilities in operation in the United States in 1966, strategically situated in a seven-state area and having a combined capacity of about 16,000 tons of ore per day. Individually, the mills have capacities ranging from 200 to 3300 tons a day.

Ease of haulage from mines, and access to power, water, supplies, and labor are economic factors that determine where the mills are placed. The direct and indirect costs of ore processing range from somewhat more than $3 per ton for large mills to $10 per ton or more in smaller units. The average cost is $6 to $7 per ton of ore, which amounts to $1.50 to $3 per pound of uranium recovered. The grade of ore is not an important cost factor in ore handling.

Uranium concentrates produced by milling are not pure enough to be used as fuel for nuclear reactors. They are, therefore, processed further, or refined, to get rid of virtually all impurities.

Refining

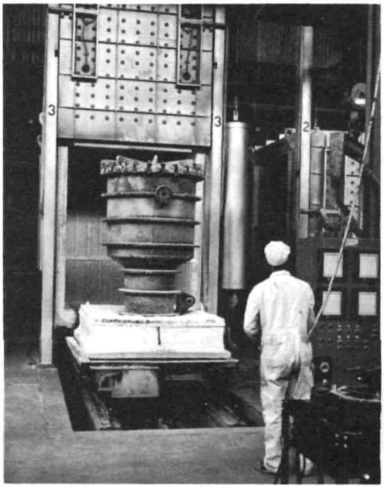
A usual first step in this process is dissolving the uranium concentrate in nitric acid. This produces an impure uranyl nitrate solution, which is mixed with a solvent,



This bank of electrolytic cells produces fluorine for a fluoride refining process.

URANIUM REFINING

Container used to transfer intermediate product.

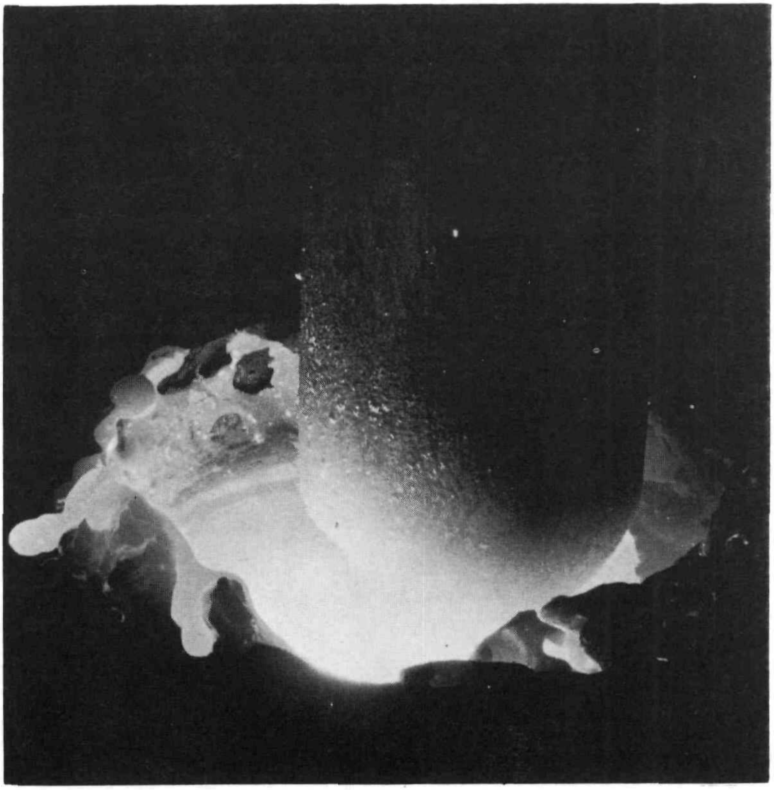


When uranium metal is required, it is produced by reacting uranium tetrafluoride ("green salt") with finely divided magnesium at high temperature. Above, a reaction vessel leaves its furnace. On the right a uranium "derby" surrounded by broken slag of magnesium fluoride.

usually tributyl phosphate dissolved in an inert hydrocarbon such as kerosene. The solvent extracts uranyl nitrate from the nitric acid solution, leaving impurities in a waste liquor.

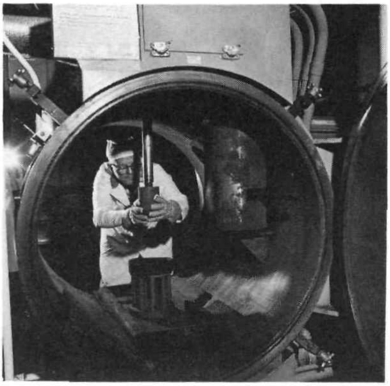
The liquids are allowed to separate, and the waste liquor, being heavier, is drawn off and discarded. The tributyl phosphate solvent containing uranium is mixed with pure water, and the uranyl nitrate transfers back from the solvent to the water. The uranium now in the water layer is pure and ready to be converted into a solid state for use as nuclear reactor fuel.

The solid form can be uranium metal, or it can be a ceramic, such as uranium carbide or uranium oxide. Whatever the state, the uranium is shaped into small pellets,

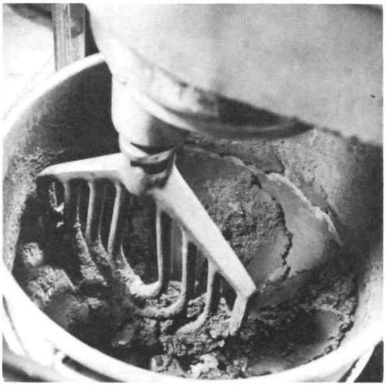


Arc melting, a step in fabrication of uranium carbide fuel elements, in progress.

FUEL ELEMENT FABRICATION



Technician adjusts carbon electrode in vacuum casting chamber, a step in fabricating uranium carbide fuel elements.



Slightly enriched uranium dioxide is mixed with a binder being granulated and compacted into fuel pellets.

A white-gloved technician loads finished fuel pellets into tubes, which will be assembled into complete fuel elements for a water-cooled reactor.

plates, or pins for use in fuel elements.* Fuel elements form the heart, or core, of a nuclear reactor.

Uranium as Reactor Fuel

In a simplified summary, here is how uranium serves as a fuel in a reactor: The reactor is housed in a steel tank called a pressure vessel. Inside the vessel is a nest or core of shaped uranium fuel elements. A coolant surrounds the core to carry off heat produced from the fission of uranium atoms—heat being the desired product in a power-producing reactor.

To start up a reactor, subatomic particles called neutrons bombard a uranium atom, splitting its nucleus. This process is called fission, and it triggers a chain reaction: As each nucleus is split, more neutrons are freed to split other nuclei. The liberated neutrons travel at extremely high speeds—too high, in fact. Slower-moving neutrons create fission more effectively, so a moderator, or slowing agent such as heavy water (water containing heavy hydrogen) is built into the reactor. (In some types of reactors, the moderator is also the coolant.)

The fission is controlled, stopped, and started again by the insertion and withdrawal of control rods. When inserted in the core, the rods† absorb neutrons, halting the reaction. As the rods are withdrawn, the fission rate steps up. Skilled operators use precisely engineered machinery to insert and withdraw the rods and can regulate exactly the output of nuclear energy.‡

Delivery of that energy is the ultimate aim of all who work with uranium.

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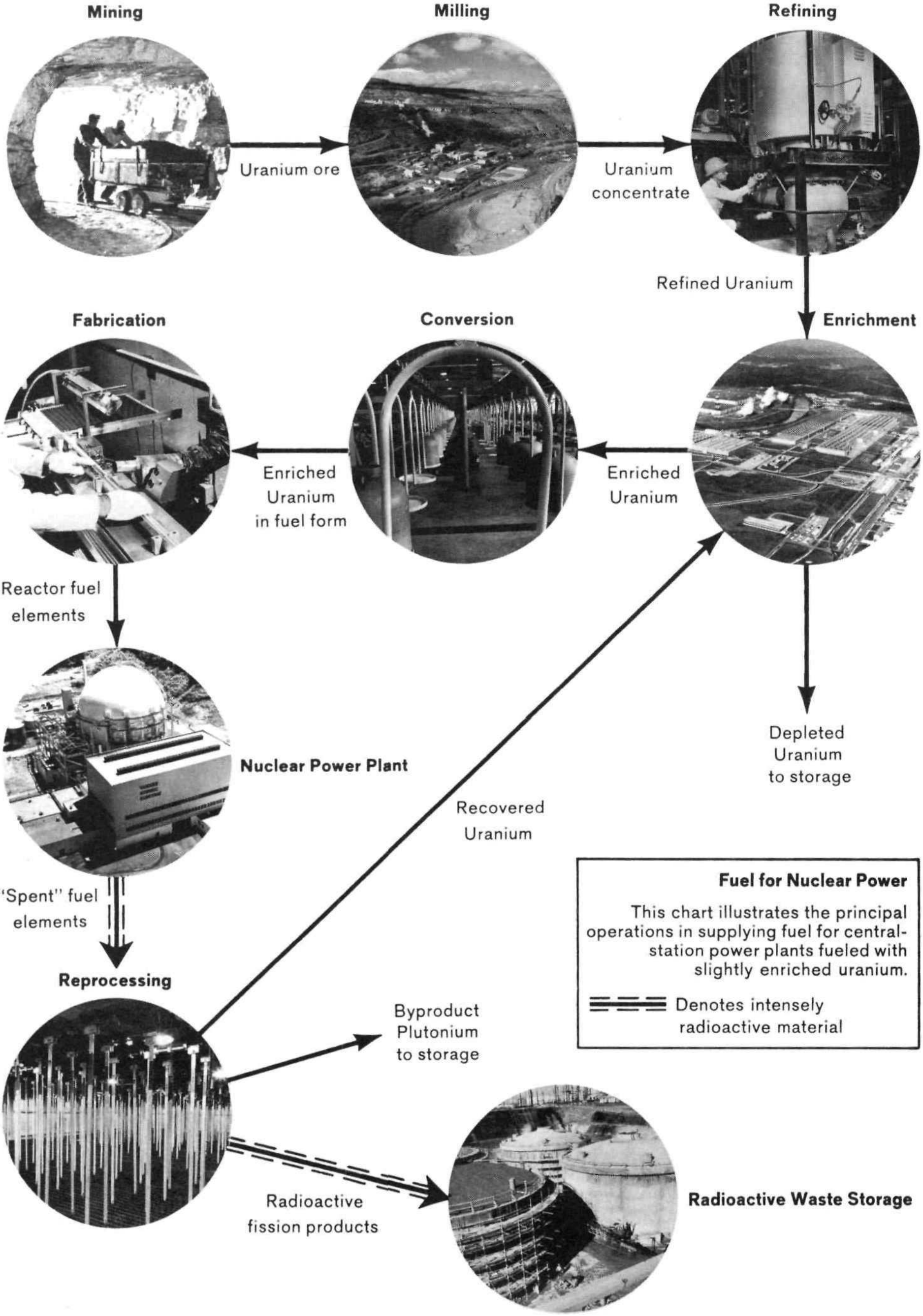
*The complex story of uranium refining, enrichment in huge gaseous diffusion plants, and fabrication of fuel elements is told in detail in *Atomic Fuel*, a companion booklet in this series.

†Made of boron or some other material that "blots up" the flying neutrons.

‡See *Nuclear Reactors*, another booklet in this series, for details of reactor construction and operation.

FUEL PROCESSING



WORKING SAFELY WITH URANIUM

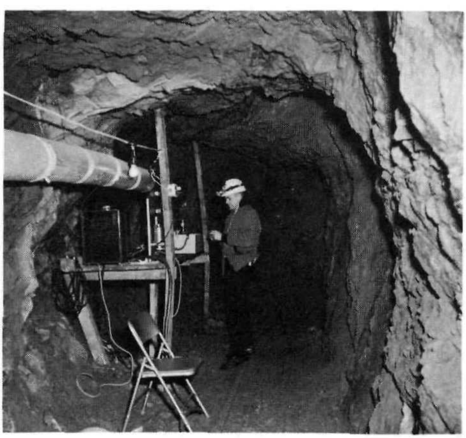
In 1966 there were about 3000 miners engaged in uranium production, and perhaps 2000 workers in mills that process the ores. Uranium producers predict that there will be substantial employment increases, perhaps doubling these numbers, in the future.

One of the prime concerns of producers and processors always has been to make their operations safe as well as efficient. All the usual hazards of the mining industry exist in uranium production. In addition, uranium is radioactive. To ensure safety, the American Standards Association (now called the USA Standards Institute) in 1960 established a new set of standards for radiation protection in uranium mines and mills.

Generally, it can be said that health and safety records in uranium mines are comparable to those in mines producing other metals, and the same comparison can be made between uranium milling operations and other milling.

The quality of the atmosphere in underground mines* is of primary importance to the health and safety of underground workers. The mine atmosphere is subject to contamination by harmful dusts and gases. Such contamination might result from drilling (dust), blasting (gases and dust),

*Open pit mining, being an aboveground operation, presents no special problems in radiation protection.



Controlled atmosphere test tunnel for radiation environment studies in a uranium mine.

materials handling (dust), use of diesel engines (exhaust gases), emission of strata gases, welding and cutting, and from mine fires. In uranium mines and some other types of mines the radiation environment must also be considered. In general, appropriate measures used to control the hazards owing to common dust and gases will serve also to reduce concentrations of radioactive materials in the mine air.

The radioactive decay of uranium leads, through a number of steps, to the production of radon gas. This gas in turn decays, forming a series of short-lived progeny, sometimes referred to as "radon daughters". These products are present in the air inhaled by miners and they tend to deposit in the respiratory system. Studies, conducted by the U. S. Public Health Service in cooperation with the AEC and State agencies, reveal that underground uranium miners develop lung cancer to a greater degree than the rest of the population, and this is believed to be due to the radioactive decay of the deposited radon daughters in the respiratory tree.

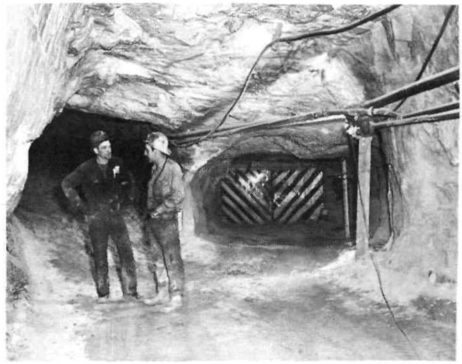
A significant reduction in the concentration of radon daughters in the air of underground mines has been achieved by the industry since 1960.

The most practical means of dealing with this problem is to replace the contaminated air in the mine with fresh air. Ventilation systems for this purpose take into account the size, number, and complexity of mine workings and the level of radon products in these workings. General considerations recommended by the Federal Radiation Council (FRC)* for this ventilation are:

1. The fresh air supply should be channeled through mine passageways so that it does not mix with contaminated air. The displaced air should be promptly exhausted aboveground at a distance from the air intake.

2. Old workings not needed for other purposes should be sealed off to inhibit the release of radon into the work areas. This will also decrease the concentration of radon daughters that can build up in the work areas.

*The FRC is the advisory body to the President of the United States on radiation matters.



Pair of ventilation doors installed in a mine to reduce radon concentration at a drift intersection.

3. Ventilation systems must be promptly altered or modified as development proceeds.

4. Air velocities through mine areas where men work must be kept within practical comfort limits.

External gamma radiation in such mines is spotty and rarely exceeds 2.5 mr (milliroentgens)* per hour. Occasionally exposure from high-grade ore pockets may require limiting personnel occupancy, but ordinarily miners are exposed to less than the maximum for occupational radiation exposure recommended by the FRC.

Over the years the AEC has cooperated with State and other Federal agencies to improve conditions in uranium mines. Recently the AEC joined in a cooperative research and development effort with the U. S. Department of the Interior's Bureau of Mines and with the U. S. Public Health Service of the Department of Health, Education, and Welfare (DHEW). Each agency conducts programs for which its staff and facilities are best suited:

1. *AEC:* Improved surveillance-monitoring equipment, characterization of mine air, and basic research supporting development of improved instrumentation.

2. *Interior:* Improvement of mine air and personal protection.

3. *DHEW:* Epidemiological studies, medical aspects, bio-effects of alpha radiation, and evaluation of control methods.

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*A roentgen (abbreviation r) is a unit of ionizing radiation.

During 1967, the AEC worked closely with the FRC in the preparation of FRC Report No. 8.* In this report were the following recommendations:

1. Occupational exposure to radon daughters in underground uranium mines be controlled so that no individual miner will receive an exposure of more than 6 WLM† in any consecutive 3-month period and no more than 12 WLM in any consecutive 12-month period. Actual exposures should be kept as far below these values as practicable.

2. Areas in underground uranium mines, whether normally or occasionally occupied, be monitored for the concentration of radon daughters in the mine air. The location and frequency of taking samples should be determined in relation to compliance with recommendation 1.

3. Appropriate records of the exposure from radon daughters in the mine air received by individuals working in uranium mines be established and maintained.

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*_Guidance for the Control of Radiation Hazards in Uranium Mining_, Staff Report of the FRC, Report No. 8 revised, Superintendent of Documents, U. S. Government Printing Office, Washington, D. C. 20402, September 1967, 60 pp., $0.40.

†Working Level (WL) is a unit defined as any combination of radon daughters in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV (million electron volts) of potential alpha energy. The concentration of radon daughters in air of unventilated underground uranium mines ranges from a fraction of a WL to several hundred WL. Exposure to radon daughters over a period of time may be expressed in terms of cumulative Working Level Months (WLM). Inhalation of air containing a radon daughter concentration of 1 WL for 170 working hours results in an exposure of 1 WLM.

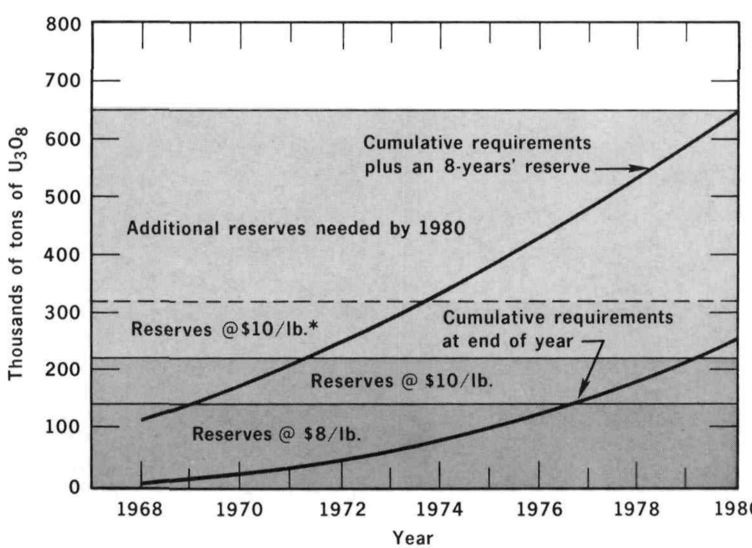
THE FUTURE OF NUCLEAR FUEL

A challenge facing the uranium industry today involves this question: Can enough material be produced when needed, not only to keep developed nations supplied, but also to help lift developing and underdeveloped areas into economic self-sufficiency?

In this connection, it is interesting that conservative estimates indicate the world's consumption of fossil fuels in the year 2000 will be more than five times the level of today. We also are told that the energy needed by the world during the rest of this century will be three times the total of all the energy consumed from the beginning of human history up to now!

It seems clear, then, that the atomic age has not arrived a moment too soon, for nuclear energy appears destined to make its greatest contribution to mankind as a supplier of electrical power in unprecedentedly large amounts. Although nuclear plants still are producing only a small percentage of America's total electrical energy, they are becoming economically competitive with fossil-fuel plants

U.S. URANIUM RESERVES AND REQUIREMENTS FOR NUCLEAR POWER



*Including by-products through year 2000

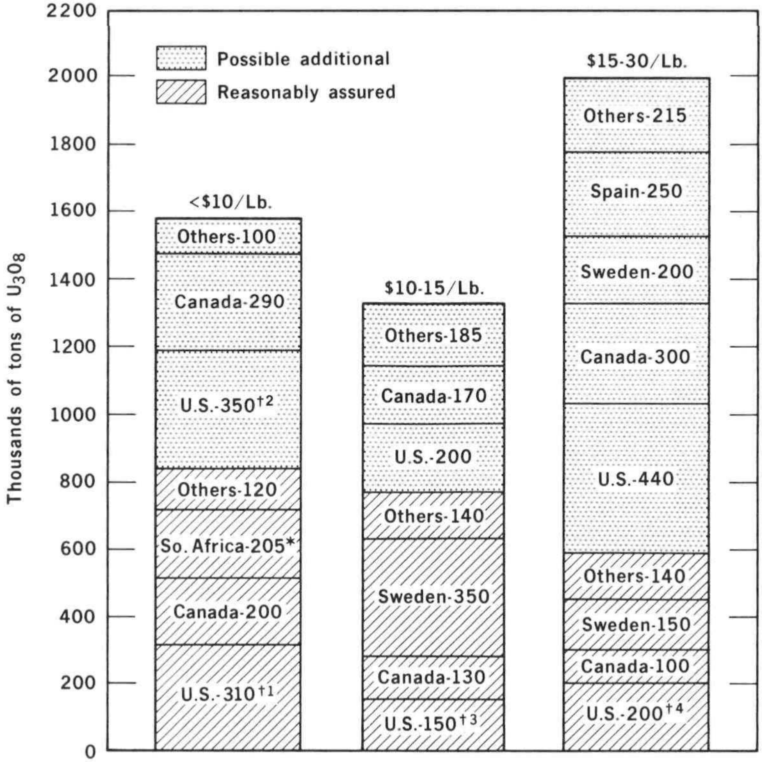
in many sections of the country, and more and more are expected to take their place with conventional power stations.

Already, there are more than a dozen central station nuclear plants operating in the United States and producing enough power for a million families. Another dozen or more are under construction or planned.*

Use of nuclear energy is accelerating on other fronts, too, and more applications are likely. Space vehicles for

*See *Nuclear Power Plants*, a companion booklet in this series, for details of these plants.

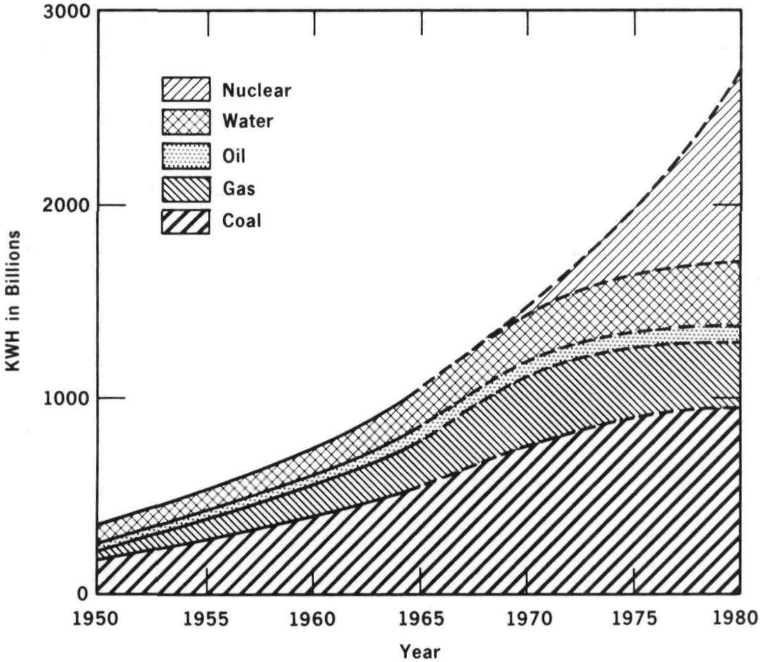
WORLD URANIUM RESOURCES
(U.S.S.R., CHINA, AND EASTERN EUROPE NOT INCLUDED)



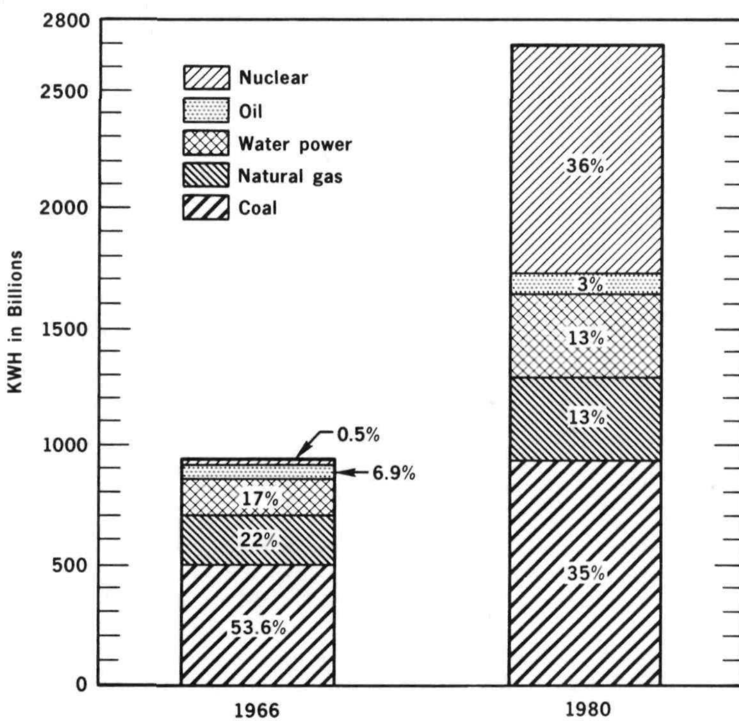
*Byproduct or co-product of gold mining; this limits annual production.

†Includes uranium estimated to be available as a byproduct of phosphate and copper mining through the year 2000: 1, 120,000; 2, 25,000; 3, 50,000; and 4, 100,000.

ANNUAL ENERGY REQUIREMENTS
FOR ELECTRIC GENERATION



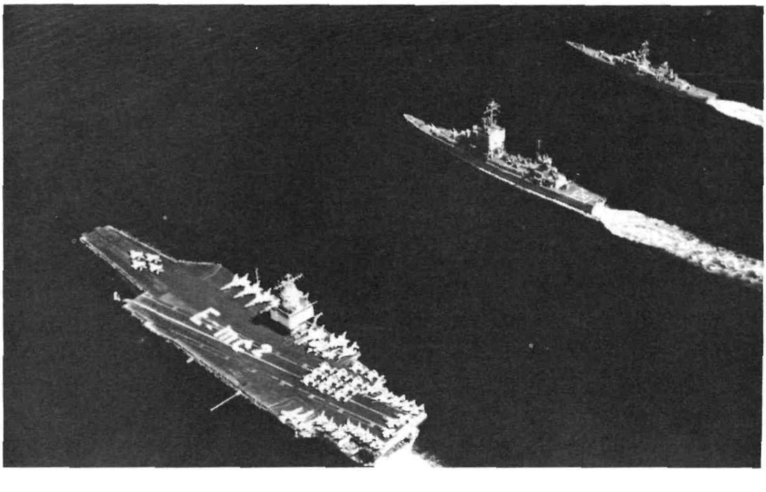
POWER SOURCES FOR ELECTRIC ENERGY
PERCENT OF TOTAL FOR EACH SOURCE



A SNAP-7B nuclear generator is hoisted inside the Baltimore lighthouse by the U. S. Coast Guard in 1964. The 60-watt generator will supply a continuous flow of electricity for 10 years without refueling.

extended manned flights will require nuclear propulsion. Nuclear auxiliary power serves space satellites, navigation buoys, and unmanned weather stations. The Baltimore lighthouse in Chesapeake Bay was the first in the world to be operated by an atomic generator.

Elsewhere on the seas, nuclear fuel provides driving power. The United States Navy has in operation about four dozen submarines and three surface ships, all propelled by atomic reactors.



The USS Enterprise, *USS* Longbeach, *and USS* Bainbridge, *all nuclear-powered vessels, in the Mediterranean Sea. The crew of the* Enterprise, *in formation, spell out Einstein's equation for mass-energy equivalence.*

The San Onofre Nuclear Generating Station near San Clemente, California, one of the new generation of nuclear power plants, with a net electrical capacity of 430,000 kilowatts. It began commercial operation in 1967.

In addition, the American Nuclear Ship *Savannah,* the world's first nuclear-powered merchant ship, has criss-crossed the globe since she was launched in the summer of 1959.

Nuclear fuel also holds a promise of providing enough water for a thirsty and growing world to drink. In 1964 President Johnson called for prompt action on a program for desalting sea water with the use of nuclear energy. Since then research has accelerated rapidly, and prospects for construction of nuclear desalting plants are considered bright, not only in the United States but in many other countries.

Other nuclear research and development is directed toward increasing basic knowledge in science and toward benefitting our daily lives through new materials and new processes based on the effects of man-made radiation. Biomedical research to determine the effects of radiation on man and use of radiation in the diagnosis and treatment of disease both employ radiation sources produced in

nuclear reactors. And there is increasing impact of atomic energy in industry and in our homes.*

Even this quick glance at the story of nuclear energy indicates its uses have been many and its future is secure. But as Dr. Glenn T. Seaborg, Chairman of the Atomic Energy Commission, has pointed out, there is no standing still in nuclear power technology. He has noted that reactors in use today are mostly pressurized-water and boiling-water types that "burn" only about 1%, or less, of their atomic fuel; that is, only the ^{235}U content of the raw uranium that is mined and processed.

"At present", Dr. Seaborg said,† "the hope for our making maximum use of our uranium and thorium fuel reserves seems to be in the development of what we call advanced converter and breeder reactors. These reactors, in conjunction with fuel reprocessing systems, will allow us to use, not a small percentage of our nuclear fuel, but esentially all of it. ... They are able to accomplish this because as they 'burn' the fraction of the fissionable isotope uranium-235 in their initial fuel, they also transmute the abundant non-fissionable isotopes, uranium-238 or thorium-232, in that fuel to fissionable plutonium-239 and uranium-233, respectively. Both these new fissionable isotopes, therefore, can be burned in place, as is done in some types of reactors, or they can be separated and reprocessed into new fuel elements for use in the same or other reactors."

The difference between the advanced converters and the breeder reactors is essentially that, while the converter creates substantial quantities of new fissionable fuel, the breeder actually produces more fissionable fuel than it consumes.

A nuclear fuel economy based on the use of these breeder reactors "offers us a way of stretching the world's supplies of uranium and thorium", Dr. Seaborg said, adding:

"It is toward such a nuclear energy economy that the government, through the Atomic Energy Commission and

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*Aspects of this impact are described in many other booklets in this series. See inside back cover for titles.

†In an address at the Second Nobel Conference, St. Peter, Minn., Jan. 13, 1966.

in partnership with our growing nuclear industry, is working."

Thus it is that Klaproth's mysterious powder, which emerged from scientific oblivion almost two centuries ago, is finally coming into its own. How it will serve mankind in the future remains to be seen.

It is clear that although uranium has traveled a long way, it still has a long way to go.

A stockpile of uranium ore.

GLOSSARY

alum any of a series of double salts, such as potassium aluminum sulfate, or potash alum.

arsenate a salt of arsenic acid.

arsenic a solid, brittle element, poisonous and light in color, found in many metallic ores.

beta rays streams of electrons sent out from some radioactive substances at very high rates of speed.

carbide a compound of carbon with other elements; a class of minerals.

carbonate a salt of carbonic acid; an important class of minerals, containing calcium carbonate.

carnotite canary-yellow to greenish-yellow potassium uranium vanadate mineral that was first discovered in the United States on the Colorado Plateau.

ceramic a pottery or earthenware material or one with the appearance of pottery or earthenware.

coffinite a black uranium silicate mineral often dispersed in and intergrown with carbonaceous material.

columbium another name for niobium, a grayish metal related to vanadium.

conglomerate a sedimentary rock that is made up of worn and rounded pebbles of other rocks cemented together.

cordillera the main mountain axis of a continent.

davidite a complex black-to-brown multiple-oxide mineral containing uranium, rare earths, iron, and titanium.

euxenite a uranium mineral, chemically a multiple oxide containing rare earths and other metals.

extrusive rock an igneous rock derived from magmas or magmatic material poured out or ejected at the earth's surface, as opposed to intrusive rocks that solidified at depth without reaching the surface.

feldspar a group of minerals composed of potassium, sodium, or calcium–aluminum silicates that occur in nearly all igneous rocks as well as in many sedimentary and metamorphic rocks. They are usually light colored.

fission splitting, cleaving, or breaking up into parts; the basic process by which nuclear energy is released.

flotation the separation of particles in a mass of pulverized ore according to their capacity for floating on a given liquid.

fluorine a pungent, corrosive, greenish-yellow gas of the halogen family; similar to chlorine.

fossil an impression or trace of a plant or an animal of past geologic ages.

fossil fuel a fuel derived from ancient plant or animal organisms preserved in the earth's crust, that is, coal, petroleum, or natural gas.

galena a principal lead ore also containing sulfur.

gamma rays electromagnetic radiation of high energy given off by some radioactive nuclei; akin to X rays but of shorter wave length.

Geiger counter a radiation detecting and measuring instrument, usually portable.

geochemistry the study of the chemical composition and changes in the crust of the earth.

geology the science that treats of the earth, its history and life, especially as recorded in rocks and rock formations.

granite a relatively coarse-grained igneous rock consisting largely of quartz, feldspar, and mica; usually white or light to medium gray in color.

half-life a measure of the amount of radioactivity in a substance; the time in which half of the atoms of a radioactive substance disintegrate to another nuclear form.

hydrocarbon a chemical compound containing only hydrogen and carbon, such as acetylene or benzene.

hydrous watery; a hydrous mineral formation is one containing water chemically combined with the mineral.

igneous rock a rock that has been formed either within the earth or at its surface by the cooling and consequent solidification of a once hot and fluid mass of rock material called magma.

ilmenite a black mineral containing iron, titanium, and oxygen.

intrusive rock formations resulting from the solidification of molten mineral material (magma) that has been forced into openings in or between layers of older rock.

ion an atom carrying an electric charge.

isotope one of two or more forms of an element, identical in chemical behavior, and distinguishable only by radioactivity or differences in atomic weight.

lignite a variety of coal, between peat and bituminous coal in hardness, usually brownish-black, non-caking, and often with the original wood texture distinct.

magma a molten rock material or mass from which igneous rocks are formed by cooling and crystallization.

massif a principal isolated mountain mass geologically uplifted as a unit.

megawatts a million watts of power.

metamorphic rock a rock derived from pre-existing igneous or sedimentary rocks by mineralogical, chemical, and textural changes caused largely by heat and pressure within the depths of the earth.

mineral any chemical element or compound occurring naturally as a product of inorganic processes; a solid, homogeneous component of rocks.

mineralogy the science of minerals.

molybdenum a white metal related to chromium; useful in alloys.

niobium a grayish metal, related to vanadium. Also known as columbium.

nitrate a salt of nitric acid; a class of minerals.

ore a mineral containing an element (especially a metal) that can be extracted profitably.

oxide a compound consisting of oxygen and usually one other element. Oxides are a common mineral class.

pegmatite a very coarse-grained igneous rock.

phosphate a salt of phosphoric acid; calcium phosphate is an important mineral source of phosphorus for fertilizer.

pitchblende a massive variety of the mineral uraninite.

plutonium a heavy, man-made radioactive metallic element used for reactor fuel.

pneumatic moved or worked by pressure of air, as a pneumatic drill.

polonium a heavy, radioactive metallic element.

potassium a soft, light alkaline metal found in many minerals.

Precambrian before the Cambrian period, which was the earliest division of the Paleozoic Era, in which plants and animals first appeared; approximately 1.9 billion years old or more.

precipitate a substance in a solid state separated from a solution as a result of a chemical or physical change caused by a reagent.

province a region containing similar geology and mineral deposits.

pyrite a mineral containing iron and sulfur.

quartz a transparent, crystalline oxide of silicon.

Quaternary refers to the second period of the Cenozoic Era and the latest period of geologic time; sometimes called the Age of Man; approximately 2 million years in extent.

radiometric referring to measurement of the intensity of radiant energy by appropriate instruments.

radium a radioactive metallic element that occurs in small quantities and is often associated with uranium.

reconnaissance a preliminary examination or survey.

rutile a mineral of titanium dioxide, usually reddish brown, and having a brilliant metallic luster.

scintillation the act of emitting sparks, gleams, or flashes; and the sparks so emitted.

sedimentary rock sandstone, shale, and conglomerate are consolidated accumulations of rock and mineral fragments that have been transported by streams or wind from eroding lands to the site of deposition. Most limestones are formed by chemical precipitation of calcium carbonate in bodies of standing water; some result from accumulations of marine organisms, frequently transported short distances by moving water.

seismic pertaining to or caused by an earthquake.

shale a very fine-grained sedimentary rock composed of consolidated muds. Shale tends to split into thin layers and is differentiated from mudstone, which is of similar composition but is massive.

silica silicon dioxide, which often occurs as quartz.

silicate one of the most abundant class of minerals; a compound containing silicon, oxygen, and a metal.

stereoscopic three dimensional; showing depth.

stope an underground opening from which ore is extracted.

sulfide a compound containing sulfur; sulfides are an important family of minerals.

tailings refuse material separated as residue in the preparation of ore.

tantalum a gray-white metal, related to vanadium.

tectonic pertaining to or originating in physical forces in the earth's crust.

thorium a naturally radioactive metal. One of its natural isotopes can be converted in nuclear reactors to a nuclear fuel.

titanium a metal, resembling silicon, found in minerals such as rutile and ilmenite.

topography the configuration of a surface, including its relief, the position of its streams, roads, etc.; the practice of detailing the physical features of a place or region.

transmute to change or convert from one form or substance to another.

tributyl an organic radical containing butane, a hydrocarbon derived from petroleum or natural gas.

uraninite a heavy brown, black, or dark gray mineral of uranium oxide with a pitchlike, dull, or glassy luster; a prolific source of uranium.

uranium the heaviest naturally occurring element. A radioactive metal that is the basic raw material of nuclear energy.

uranyl a bivalent radical, UO_2, which behaves as an element in many uranium compounds.

vanadate a salt of vanadic acid.

vanadium a soft, white metal, related to phosphorus; valuable as an alloy.

vein a fissure in a rock formation filled with mineral matter, or a bed of useful mineral.

volcanic pertaining to a volcano; rock formed from molten lava.

zirconium a metal, related to titanium, found in minerals only in combination with other metals.

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Uranium Country, Kathleen Bruyn, University of Colorado Press, Boulder, Colorado 80304, 1955, 165 pp., $2.00.

Mineralogy and Geology of Radioactive Raw Materials, E. William Heinrich, McGraw-Hill Book Company, Inc., New York 10036, 1958, 654 pp., $18.50.

Motion Pictures

Available for loan without charge from the AEC Headquarters Film Library, Division of Public Information, U. S. Atomic Energy Commission, Washington, D. C. 20545 and from other AEC Film libraries.

Atomic Gold Rush, 12½ minutes, black and white, 1956. Produced by The Handel Film Corporation. Uranium prospecting is described from initial surveys by plane and on foot through staking a claim, sample core drilling, core analysis, and mining.

The Fifth Fuel, 22 minutes, color, 1967. Produced by the AEC's Oak Ridge Operations Office. This film illustrates preparation of enriched uranium from mining through chemical and metallurgical processing to the extrusion of fuel elements. Safety features throughout the processes are emphasized.

Giant of the Earth, 26 minutes, black and white, 1955. Produced by the Colorado Mining Association. Uranium prospecting and mining on the Colorado Plateau are covered as well as the AEC activities at Grand Junction, Colorado.

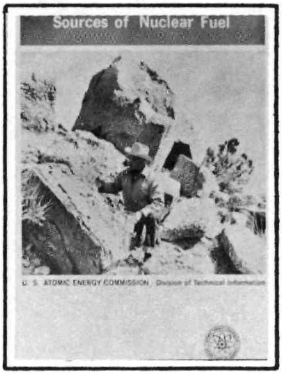
Guardian of the Atom, 28½ minutes, color, 1967. Produced by the AEC's Division of Public Information. This film, describing the activities of the Atomic Energy Commission, has extensive footage on uranium mining, milling and refining.

The Petrified River, 28 minutes, color, 1956. Produced by the Union Carbide Corporation and the U. S. Bureau of Mines under the technical direction of the AEC. This story of uranium for all audience levels covers deposition during prehistoric times, prospecting on the Colorado Plateau, mining, milling, and the use of the atom to produce power and radioisotopes.

Production of Uranium Feed Materials, 28 minutes, color, 1959. Produced by the AEC's Oak Ridge Operations Office. This semitechnical film for high school and college level audiences shows step-by-step processing of uranium ore concentrates in the fuel materials plants at Fernald, Ohio, and Weldon Spring, Missouri.

The Search—Uranium Prospecting and Mining, 23 minutes, black and white, 1955. Produced by the Columbia Broadcasting System and the Colorado Mining Association. This nontechnical film for intermediate through college level audiences tells the story of the exploration, prospecting, and mining of uranium ores in the Colorado Plateau.

ABOUT THE COVER



A prospector, armed with a Geiger counter and hammer, moves among rocks in northern New Mexico in search of uranium-bearing ore, the fundamental source of nuclear energy for all purposes. This prospector, a Laguna Indian, was employed by a mining firm to seek uranium on his tribe's land, before aerial exploration revealed important deposits there. A large part of American uranium has come from New Mexico, Arizona, Utah, and Colorado.

ABOUT THE AUTHOR

ARTHUR L. SINGLETON, JR., is a veteran writer who has been employed since 1960 in the field of industrial communications after a long career as a newspaperman in Petersburg, Virginia, Baltimore, and Washington, D. C. He holds a bachelor's degree from the University of Richmond, an M.A. in history from The George Washington University, and has taken additional graduate studies. A lecturer in journalism and public relations at the University of Maryland, he is the author of a number of articles, booklets, and other publications on a variety of subjects.

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23	*Uranium Ore Processing,* John W. Clegg and Dennis D. Foley (Eds.), Addison-Wesley Publishing Company
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